15 NAVIGATION, LANDING, AND LIGHTING SYSTEMS

The FAA, the Department of Defense (DOD), and nonfederal agencies operate more than 4,300 ground-based electronic navigational aides (Navaids[1]) that broadcast navigation signals within a limited area. This network of Navaids enables users with suitable avionics to navigate en route and safely fly nonprecision (course guidance only) and precision approaches (course and glide path guidance) in most meteorological conditions.

The FAA also provides a variety of approach lighting systems that enhance pilot transition from instrument reference to visual reference for landing. Operational requirements, including the specific approach to be flown, dictate the types and configuration of the approach lighting system for a particular runway. Approach lighting systems enable Category (CAT) I precision instrument approaches to be flown to one-quarter-mile lower visibility minimums.

The navigation and landing system will evolve from ground-based Navaids to a satellite-based system that will consist of the Global Positioning System (GPS) augmented by the Wide Area Augmentation System (WAAS) and the Local Area Augmentation System (LAAS). The satellite-based system will meet the demand for additional navigation and landing capabilities and improve safety while avoiding the cost of replacing, expanding, and maintaining many of today's ground-based Navaids.

The satellite-based navigation system will provide the basis for NAS-wide direct routing, provide guidance signals for precision approaches to most runway ends in the NAS, and reduce the variety of navigation avionics required aboard aircraft. Operational efficiency and safety will be improved by adding more than 4,200 precision approaches (and an additional 4,200 nonprecision approaches) at many airports lacking such capabilities today (see Section 28, Airports).

In order to take advantage of the opportunity the new capabilities offer to significantly increase capacity and to meet FAA forecasts for increased traffic, severely congested airports may require additional airport development (in terms of both clearance categories and pavement). Aviation system users and airports at low-capacity locations who want to take advantage of new opportunities may incur additional airport development costs.

DOD plans to replace the current GPS satellite constellation beginning in 2005. The new satellites will feature an additional frequency (i.e., a second frequency) to improve performance for civil use.

After sufficient time to allow for installation of satellite-based avionics and sufficient experience with WAAS and LAAS operations, a phase-down of ground-based navigation systems will begin. The phase-down is expected to begin in 2005. The exact timetable and extent of Navaid decommissioning will depend on the performance of the satellite-based systems, international agreements, and user acceptance.

Congress has directed a slowdown in WAAS until technical and programmatic uncertainties are resolved. Initial operating capability (IOC) for WAAS is expected to begin in 2000. IOC is expected to provide en route navigation and nonprecision and precision approach capability with some operational restrictions. Incremental improvements after IOC will enable pilots to use GPS/WAAS avionics for all phases of flight during instrument meteorological conditions.

There may be a need for a limited number of additional instrument landing systems (ILSs) to support new runways at capacity-constrained airports. These ILSs would be installed on an as-needed basis during the transition. Because GPS/WAAS is expected to provide service equivalent to a CAT I ILS, emphasis would be in supporting CAT II and III[2] requirements.

During phase-down, the reduced network of ground-based facilities (very high frequency

1. A Navaid is any visual or electronic device, airborne or on the surface, that provides point-to-point guidance information or position data to aircraft in flight, page 299, 1995 Airman's Information Manual/Federal Aviation Regulations (AIM/FAR).
2. Lowest authorized ILS minima are: CAT I, 200-foot decision height and 1,800 to 2,400-foot runway visual range (RVR); CAT II, 100-foot decision height and 1,200-foot RVR; CAT IIIa, no decision height and 700-foot RVR; CAT IIIb, no decision height and 300-foot RVR (Reference: FAA Order 8400.10 U.S. Standard for Terminal Instrument Procedures).

(VHF) omnidirectional range/distance measuring equipment (VOR/DME), nondirectional beacons (NDBs), tactical air navigation (TACAN), or ILSs)) will enable users who are not equipped with satellite-based avionics to continue to fly in the NAS. In some areas, these aircraft will need to follow more circuitous routes than aircraft with satellite-based avionics. In the event of an unexpected localized loss of satellite-based services, aircraft equipped exclusively with satellite-based avionics in airspace with radar services will be vectored to visual conditions, to areas where Navaid reception provides backup, or to regions unaffected by the loss of the satellite navigation (SAT NAV) signal.[3]

Studies are underway to: (1) determine how many ground-based facilities should remain in service to provide a temporary/permanent redundant navigational capability, and (2) determine whether GPS/WAAS can be the only navigation capability carried aboard an aircraft and provided by FAA. The NAS Architecture will be revised in accordance with the study results.

15.1 Navigation and Landing Architecture Evolution

The following four steps present the evolution from ground-based to satellite-based Navaids:

- Step 1: Navigation and Landing Architecture (Current–1999)
- Step 2: Implementation of WAAS (2000–2002)
- Step 3: Completion of WAAS; Implementation of LAAS; Start Phase-Down of Ground-Based Navaids (2003–2007)
- Step 4: Completion of Phase-Down of Ground-Based Navaids (2008–2015).

15.1.1 Navigation and Landing Architecture Evolution—Step 1 (Current–1999)

Figure 15-1 illustrates the current navigation architecture. The VOR/DME network provides users with a primary means of navigation for en route flight and nonprecision approaches. The network consists of more than 1,000 VOR, VOR/DME, or VORTAC (VOR co-located with TACAN) facilities. The DOD operates an additional 30 such facilities at terminal locations.

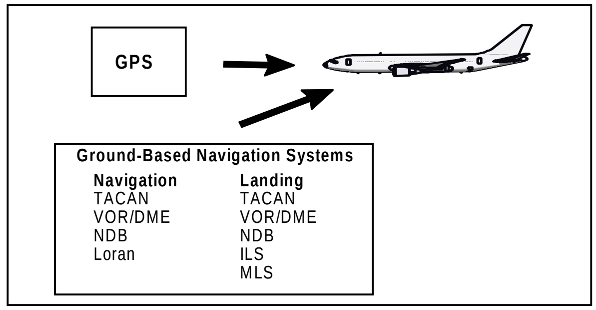

Figure 15-1. Current Navigation Architecture

To supplement the VOR/DME network, the FAA operates more than 700 NDBs, and the DOD about 200 NDBs. NDBs are used as compass locators in conjunction with some ILSs and for nonprecision approaches at low-traffic airports without convenient VOR approaches. NDBs are also used for en route operations in some remote areas and for transitioning from oceanic to domestic en route airspace.

The FAA operates more than 600 TACAN systems to provide air navigation for most military aircraft. DOD also operates more than 150 TACANs. The U.S. Coast Guard operates the Loran-C system, which can be used for en route navigation in the NAS, provided another system (VOR/DME, NDB, or TACAN) is carried onboard. Current Loran-C avionics do not support instrument approach operations.

The FAA and DOD operate two types of precision approach Navaids: ILS and a limited number of microwave landing systems (MLS). The FAA operates about 1,000 ILSs and 26 MLSs. DOD operates 180 ILSs and precision approach radars.

DOD operates the GPS satellite constellation. GPS provides worldwide, all-weather, 3-dimensional position, velocity, and time data to a variety of civilian and military users. GPS is approved for en route navigation and nonprecision approaches, provided that another system (VOR/DME, NDB, or TACAN) is carried onboard. Certain GPS receivers are approved for navigation in oceanic and remote airspace; no other navigation systems are required onboard.

3. While some surveillance systems will evolve to make use of the GPS signals, surveillance radars will not be dependent on GPS (see Section 16, Surveillance).

The FAA operates and maintains approximately 1,000 approach lighting systems. They consist of a configuration of lights starting at the landing threshold and extending into the approach area. Some systems include sequenced flashing lights that appear to the pilot as a ball of light traveling toward the runway at high speed.

A variety of approach lighting system configurations exist. The most common are the medium-intensity approach lighting systems with runway alignment indicator lights (MALSR) to support CAT I precision approaches and the high-intensity approach lighting system with sequenced flashing lights (ALSF-2) to support CAT II and CAT III precision approaches.

The FAA also operates and maintains approximately 1,700 visual glide slope indicators. These consist of 1,350 visual approach slope indicators (VASIs) and 350 precision approach path indicators (PAPIs). Visual glide slope indicators provide visual reference to pilots as they approach the runway for landing. Currently, the FAA is replacing the VASIs with PAPIs because PAPIs conform to International Civil Aviation Organization (ICAO) international standards while VASIs do not.

Depending on their operational needs and financial constraints, users choose to equip their aircraft with a variety of avionics for navigating in the NAS. These include:

- *GPS:* Provides navigation in oceanic and remote airspace. It can be used for en route navigation and nonprecision approaches in domestic airspace, provided another system (VOR/DME, NDB, or TACAN) is carried onboard.
- *VOR/DME:* Provides navigation guidance for en route navigation and nonprecision approaches (TACAN for DOD).
- *ILS:* Provides navigation guidance for CAT I/II/III precision approaches.
- *Automatic Direction Finder (ADF):* Provides direction to an NDB ground transmitter. One use is for a nonprecision instrument approach, based on tracking to or from the beacon, without an electronic glideslope.
- *Loran-C:* Can be used for en route navigation, provided another system (VOR/DME, NDB, or TACAN) is carried onboard. Current Loran-C avionics do not support instrument approach operations.
- *Inertial Systems:* Are self-contained systems used in many military and transport aircraft for oceanic and domestic en route navigation.
- *MLS:* Provides a limited number of CAT I precision approaches and some nonprecision instrument approach operations.

Nonfederal organizations (i.e., airport authorities, states, airline operators, etc.) fund and operate approximately 1,500 Navaids at locations that do not qualify for federal funding due to insufficient traffic. These organizations maintain and operate the Navaids, and the FAA inspects and verifies their safe operation under the nonfederal program. The nonfederal Navaids include approximately: 200 ILSs, 1,000 NDBs, 60 VORs, 100 DMEs, 10 MLSs, and 50 to 100 lighting aids of various types.

15.1.2 Navigation and Landing Architecture Evolution (Implementation of WAAS)—Step 2 (2000–2002)

The implementation of satellite navigation will help the NAS to meet increasing aviation traffic and will allow a reduction in the number of ground-based Navaids. The GPS signal must be augmented to ensure accuracy, integrity, continuity, and availability (see Figure 15-2). WAAS will augment the GPS signal for en route and terminal navigation and instrument approaches. GPS, augmented by WAAS, will provide instrument approaches to CAT I minima at most runway ends in the NAS (where obstacle clearance, runway,

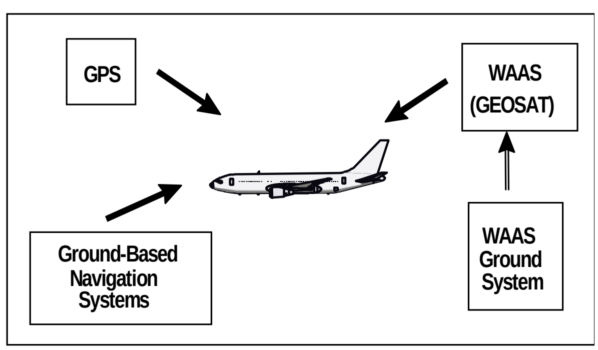

Figure 15-2. GPS Augmented by WAAS

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lighting, and signage requirements are met). Because WAAS can provide precision approaches to new runways, to CAT I minima if required, the need for new ILS CAT I approach equipment will be eliminated. In addition to added instrument approaches, users will benefit from increased area navigation and more direct routing.

WAAS consists of master stations and precisely surveyed reference stations interconnected by a terrestrial communications infrastructure. Communications from the ground master stations are broadcast to aircraft via WAAS geostationary satellites (see Figure 15-3).

To improve GPS accuracy, WAAS geostationary satellites (GEOSATs) will broadcast differential corrections for ionospheric delay, satellite position, and satellite clock errors. The reference stations monitor the GPS and WAAS signals to ensure system integrity and report any anomalies to the master station. GEOSATs broadcast status to the aircraft avionics. Availability is improved because WAAS geostationary satellites appear to the avionics as additional GPS satellites.

WAAS will be implemented in phases, with operational capability improving at each phase. The initial phase, which consists of 25 reference stations, 2 master stations, and GEOSAT uplink stations, has been installed. It is in the process of being networked and tested to provide an initial operating capability (IOC) for flight operations in 2000. The IOC will provide signals for domestic en route navigation and nonprecision and precision instrument approaches with operational restrictions within a limited WAAS coverage area.

During this phase, WAAS-equipped aircraft will be able to fly instrument flight rules (IFR) without having other navigation avionics aboard (e.g., VOR/DME or NDB). However, procedural or operational restrictions may affect the availability of GPS/WAAS approaches in some areas of the country. Flights in these areas will need to rely on existing procedures and VOR/DME or NDB.

The initial phase of WAAS will provide CAT I precision approach capability within a limited coverage area. However, the precision approach minima initially authorized may be somewhat higher than current CAT I ILS minima while both the FAA and aircraft operators gain experience. Procedural or operational restrictions may affect approach availability.

Decisions on approach minima will need to be made at some locations where ½-mile visibility is not necessary, thus avoiding the high cost of instrument approach lighting systems. During this initial phase, pilots who need to plan for an IFR alternate airport may need to rely on visual approach procedures or on Navaids, such as ILS, VOR/DME, or NDB, similar to operations today. The initial WAAS precision approach coverage area will be limited, depending on the location of WAAS reference stations and the coverage of WAAS satellites. The coverage volume will gradually increase as data are collected to substantiate GPS/WAAS ionospheric performance.

An interim phase will provide additional master and reference stations to improve WAAS coverage, performance, and real-time availability. Automated notice to airmen (NOTAM) service with predictive capabilities will become available.

Instrument approach procedures based on GPS/WAAS will be published by WAAS IOC. Subsequently, 500 procedures will be published each year until requirements are met. In addition, 500 GPS nonprecision approach procedures will be developed annually.

15.1.3 Navigation and Landing Architecture Evolution (Completion of WAAS, Implementation of LAAS, Start Phase-Down of Ground-Based Navaids)—Step 3 (2003–2007)

In its final phase, WAAS will achieve full operating capability (FOC) by the addition of ground monitoring and control stations and geosatellites. Hardware installed earlier in the program will be upgraded. WAAS will then provide performance equivalent to ILS CAT I with a level of service that is sufficient to replace existing VOR/DME and NDB facilities and most CAT I ILS facilities. Also at FOC, the interim procedural and operational restrictions imposed at IOC will be removed.

To provide additional precision approaches, LAAS will be installed to augment GPS in this step. LAAS will augment GPS at a planned 112 airports in the NAS to provide CAT II/III precision approaches (see Figure 15-4).

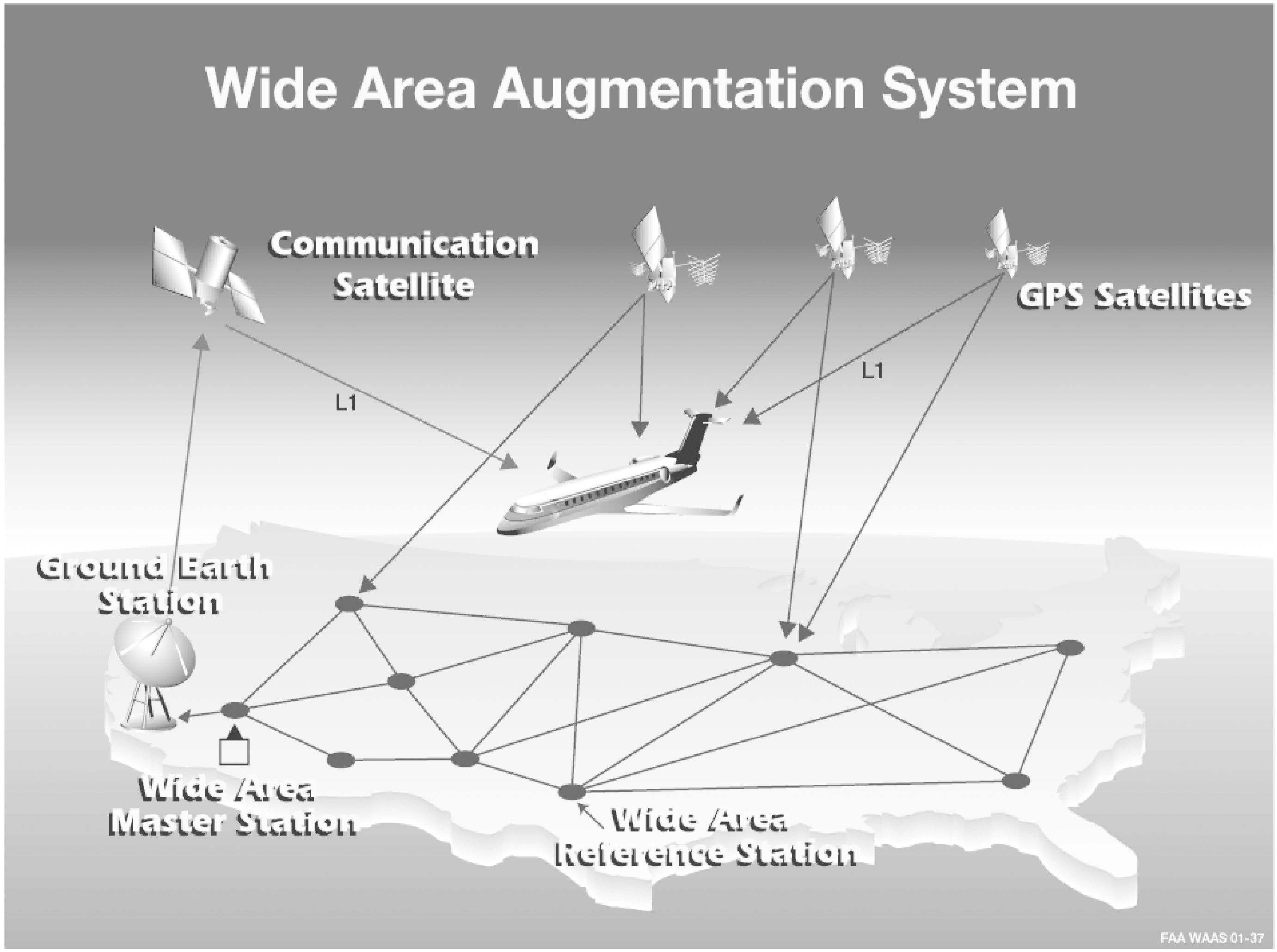

Figure 15-3. Wide Area Augmentation System

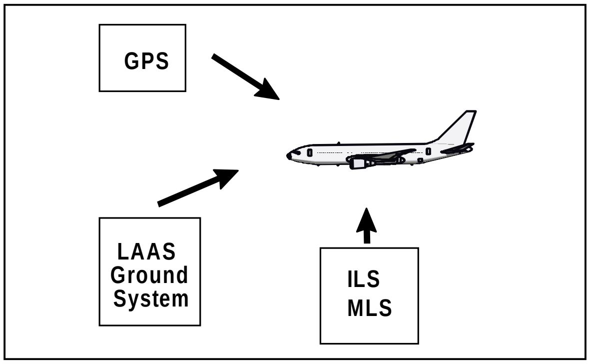

Figure 15-4. GPS Augmented by LAAS

LAAS will also provide CAT I precision approaches at a planned 31 airports that are either outside of WAAS coverage (17) or have high activity that requires a higher availability than WAAS can support (14). LAAS capability does not require WAAS, and its implementation schedule is independent of the WAAS program. The LAAS architecture is shown in Figure 15-5.

Suitable approach lighting systems will be installed to support additional precision instrument approach procedures enabled by LAAS.

A LAAS installation is anticipated to consist of a precisely surveyed ground station with multiple GPS receivers, a VHF link, and one or more pseudolites[4] to increase availability. The LAAS ground station will calculate differential accuracy corrections based on the station's location and on measurements taken from each GPS satellite. It will then broadcast the corrections on VHF radionavigation frequencies, together with an integrity message, to aircraft within a radius of 20 to 30 nmi from the airport. LAAS is expected to be significantly more affordable to install, operate, and maintain than ILS. One LAAS will allow CAT II/III precision approaches at all runway ends at an airport, topology and lighting equipment permitting. This is a savings compared to ILS technology, which requires each runway end to have an ILS.

LAAS is expected to support ground operations such as runway incursion avoidance and airport surface navigation and surveillance. For additional information about how LAAS will be used in the NAS, refer to Section 16, Surveillance; Section 18, Avionics; Section 23, Terminal; and Section 24, Tower and Airport Surface.

The FAA's plans for the transition to SAT NAV technology and for the phaseout of ground-based Navaids will be periodically reevaluated. An FAA-funded risk assessment study is being conducted to determine whether satellite navigation technology can serve as an only means of radionavigation in the NAS. Assessment results are expected in early 1999. If it is determined that GPS/WAAS/LAAS cannot satisfy the performance requirements to be the only navigation system installed in an aircraft or provided by the FAA, then it may be necessary to maintain a reduced network of ground-based Navaids beyond 2010 to support satellite navigation.

As soon as circumstances permit, the FAA plans to begin reducing the number of ground-based Navaids in a two-step phase-down. Criteria for identifying the Navaids to be shut down will be published well ahead of the first step.

Prior to starting the first step of phase-down, the FAA, in conjunction with users, expects to determine whether the phase-down schedule should be adjusted. Preliminary analysis indicates that approximately 350 VORs and 300 ILSs would be shut down in the first step, leaving sufficient ground-based Navaids to enable users who are not equipped with satellite-based avionics to continue to fly in the NAS.

15.1.4 Navigation and Landing Architecture Evolution (Completion of the Phase-Down of Ground-Based Navaids)—Step 4 (2008–2015)

Completion of the first step of the ground Navaid phase-down is expected in 2008. A second step, slated for 2009 to 2010, would shut down approximately 100 VORs, 250 ILSs, and 470 NDBs.

The remaining Navaids (approximately 600 VOR/DMEs, 500 ILSs, and 280 NDBs) would be sufficient to support en route navigation and instrument operations at the busier airports in the NAS (about 2,400) should there be a disruption in GPS/WAAS service.

4. A pseudolite is a ground-based transmitter of GPS-like signals that are used for ranging. The number and placement of pseudolites will depend on the topology of each site.

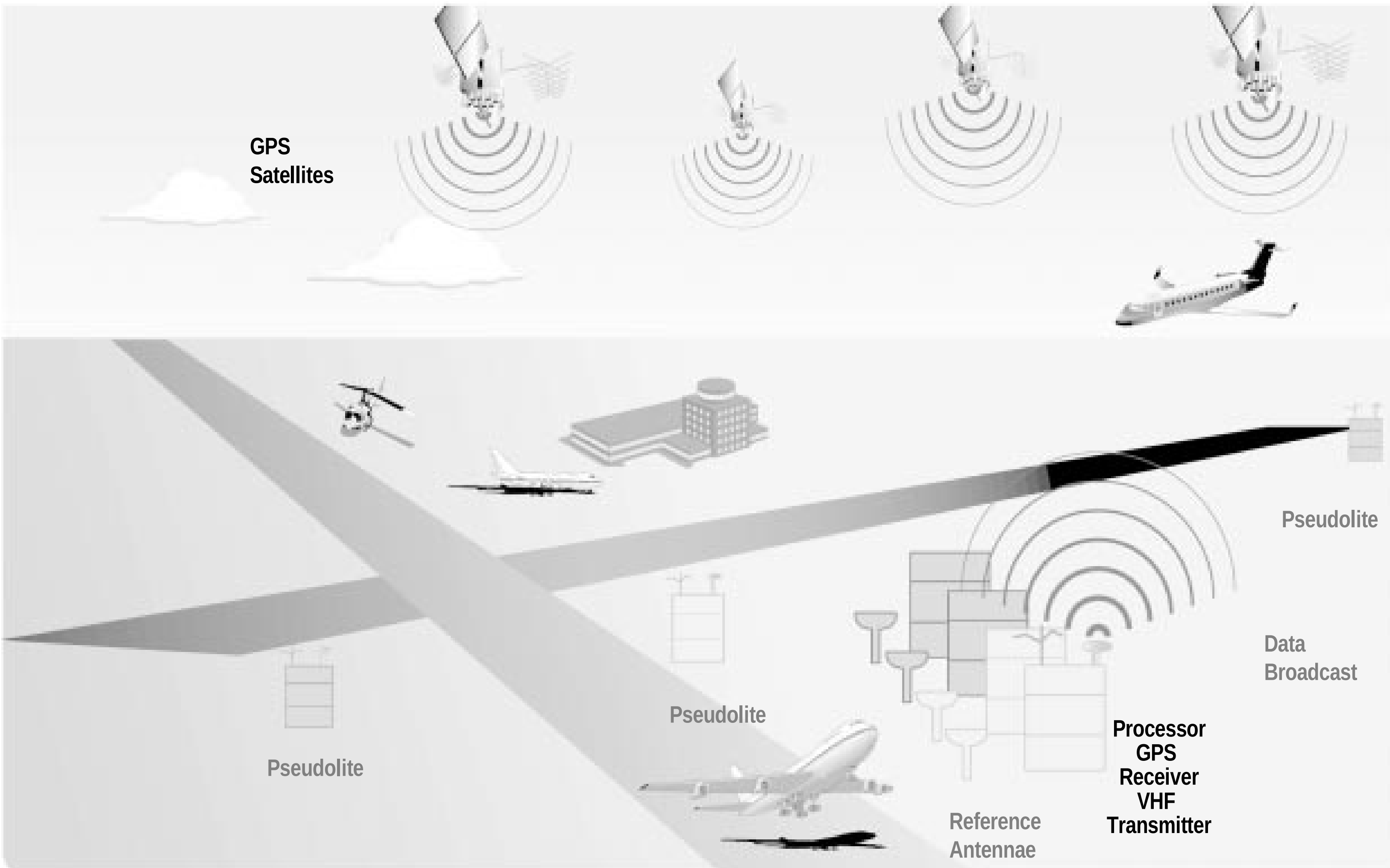

Figure 15-5. LAAS Architecture Overview

Because precision landing services will eventually depend primarily on the use of GPS signals augmented by WAAS and LAAS differential correction signals, it is clear that these systems need to be protected from harmful interference. The FAA[5] is currently working with DOD to develop safety and system security countermeasures for satellite-based navigation and landing systems to prevent or mitigate interference such as jamming. Integrity of the satellite-based system will be assured prior to phasing out ground-based Navaids. New GPS satellites with a second civil frequency capability will be launched during this period to replace all the current GPS satellites. The addition of the second civil frequency will mitigate the effects of unintentional jamming and could also provide increased accuracy by means of the direct measurement of ionospheric delay by aircraft dual-frequency avionics.

Ground-based systems are expensive to procure, install, and maintain. Current NAS planning includes sufficient funding to maintain the Navaid infrastructure in accordance with near-term aviation growth and with the navigation and landing architecture described herein (i.e., with a Navaid phase-down).

However, if users do not convert to GPS-based avionics, and if plans to phase out ground-based Navaids are not realized, then Navaids reaching the end of their service life will need to be replaced.

Currently, it costs the FAA $170M annually to operate the ground-based system. Replacing the ground-based systems would require an estimated $2.61B investment.[6] Additionally, if users do not convert to GPS-based avionics, more ground-based Navaids will be needed over time to support aviation growth. For example, more than 200 airport authorities have requested, and are eligible for, new ILS installations.[7]

Substantial investment would be required to install or replace Navaids designed to support a 1950’s operational concept. Such an investment would not improve NAS operations, whereas WAAS and LAAS support direct routes and enable more flexible use of airspace.

After satellite-based systems are deployed and certified, and before other Navaid systems can be phased out[8] (see Figure 15-6), the following three essential prerequisites must be met:

System Performance. New technology must meet service requirements. This will be determined through analyses, flight tests, and operational experience.

Operational/Economic Benefits. There must be sufficient operational and economic incentive before users will invest in satellite-compatible avionics. Economic benefits include using a WAAS or a WAAS/LAAS receiver in lieu of multiple avionics, fuel savings from user-preferred routes, and direct routes in high-density areas. Operational benefits include instrument approaches at new airports and runway ends and enhanced efficiency because of additional approaches. GPS with WAAS augmentation can provide vertical guidance for all future instrument approach procedures—greatly increasing flight safety. In the past, pilots readily accepted and began using satellite-based navigation soon after it was certified as a supplemental means of navigation. Additional user implications and costs are described in Section 18, Avionics.

Transition Period. The transition period begins with the initial operational availability of GPS/

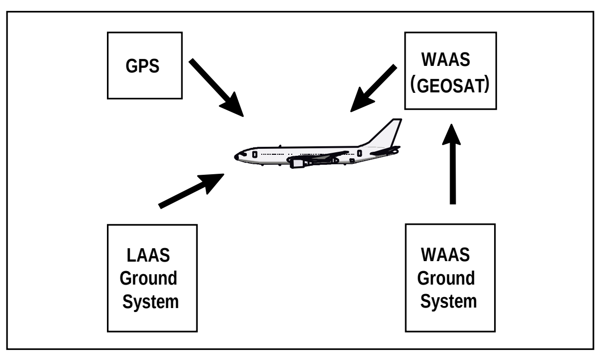

Figure 15-6. Ground-Based Navaids Phased Out

5. The FAA integrated product team and the NAS Information Security Program.
6. FAA cost estimate.
7. Reference: Mission Need Statement 120, Establishment of ILS and Associated Aids, paragraph 9(b)(2), 2 Feb 1993.
8. Under current law, ground-based Navaids can be transferred to nonfederal sponsors who can continue to operate them. However, the FAA needs to recover valuable VHF spectrum to use for other safety-critical services.

WAAS and associated avionics in 2000. Users must have time to recoup their investment in current avionics, and the FAA must have time to develop and publish instrument approach procedures for use with the new technology. A reasonable compromise must be reached between the FAA's desire for a rapid transition and the aircraft operator's desire to use current equipment as long as possible.

15.2 Summary of Capabilities

The existing ground-based navigation and landing capabilities will evolve to a satellite-based system using GPS and related augmentation systems (see Figure 15-7). GPS/WAAS will become the primary means for en route and terminal navigation and will provide CAT I approach capability to airports. GPS/LAAS will provide CAT II and III precision approaches to selected airports. LAAS will also provide CAT I approaches to airports outside WAAS coverage and to a few high-activity airports. As WAAS/LAAS coverage extends throughout the NAS, the ground-based navigation and landing systems will be phased down, leaving sufficient Navaids to support principal air routes and instrument approaches at high-activity airports, should there be a GPS/WAAS service outage.

In its initial phase, WAAS will provide a functional verification system for developing test and evaluation procedures and conducting WAAS system-level testing and operational testing. During this time, GPS can be used for en route navigation and precision approaches in a limited coverage area; however, some additional procedural or operational restrictions may be necessary. Subsequent phases will incorporate additional ground hardware, software upgrades, geosatellites, and improved operational control until WAAS FOC is achieved. WAAS will then satisfy requirements for using GPS for departure, en route, and terminal area navigation and for CAT I precision approaches. The operational and procedural restrictions initially imposed will not be necessary.

LAAS is expected to also provide the all-weather capability needed for precise airport surface navigation. A single LAAS will provide CAT II/III precision approach capability to all runways at an airport. LAAS capability and deployment is independent of WAAS.

15.3 Human Factors

Until now, only a relatively few users, equipped with flight management computer systems or Loran-C, had a flexible, point-to-point navigational capability. In the immediate future, however, any aircraft equipped with GPS or WAAS avionics will have the capability to navigate directly between any two points, independent of Navaids or traditional published routes.

Pilots seeking to take full advantage of this direct routing capability pose a significant challenge to the air traffic control (ATC) system and to controllers, who are tasked with ensuring safe separation between aircraft while facilitating efficient traffic flow. New procedures, automation tools, and training will be necessary to help controllers

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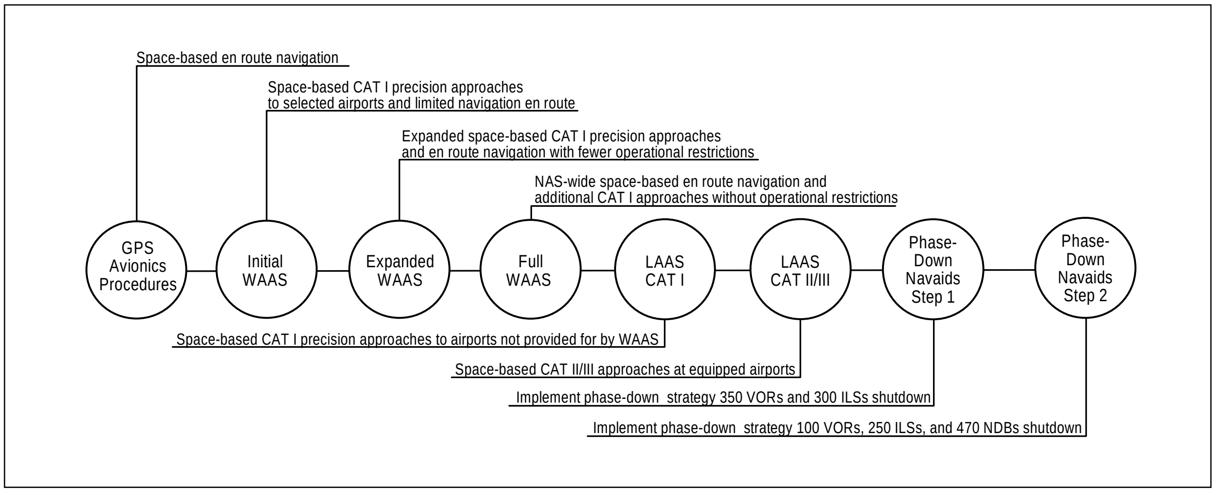

Figure 15-7. Navigation and Landing Capabilities Summary

and pilots manage these capabilities safely and efficiently.

New cockpit displays, including moving maps and cockpit display of traffic information (CDTI), are either available or in development. Traditional fixes used by controllers and pilots will be replaced by pilot-defined waypoints. The georeferences for navigation and surveillance will change. Additionally, new GPS-based instrument approach procedures are being developed. The Safe Flight 21 Program is intended to provide the means for developing and/or testing the equipment features and the pilot and controller procedures needed to realize the full benefits of GPS/WAAS and LAAS.

15.4 Transition

The navigation and landing transition schedule is shown in Figure 15-8. Specific activities associated with the navigation and landing architecture are:

- Safe Flight 21 Program demonstration of prototype LAAS at demonstration sites
- GPS/WAAS backup analysis
- WAAS deployment (IOC/FOC)
- LAAS deployment
- Ground-based Navaids phase-down strategy.

15.5 Costs

The FAA estimates for research, engineering, and development (R,E&D); facilities and equipment (F&E); and operations (OPS) life-cycle costs for navigation, landing, and lighting systems architecture from 1998 through 2015 are presented in constant FY98 dollars in Figure 15-9.

15.6 Watch Items

The evolution of the navigation architecture depends on policy decisions, regulations, equipment certification, standards development, and performance factors. These include:

- Availability of GEOSATs (Additional satellites are needed for WAAS to achieve its full operational capability. A study will evaluate the options available for providing the additional satellites. Funding to lease the additional satellite capability is programmed to begin in FY02 or 03.)
- Studies on redundant Navaids (The FAA is studying what redundant navigational capability may be required in the event of a GPS outage.)
- Certified, affordable avionics

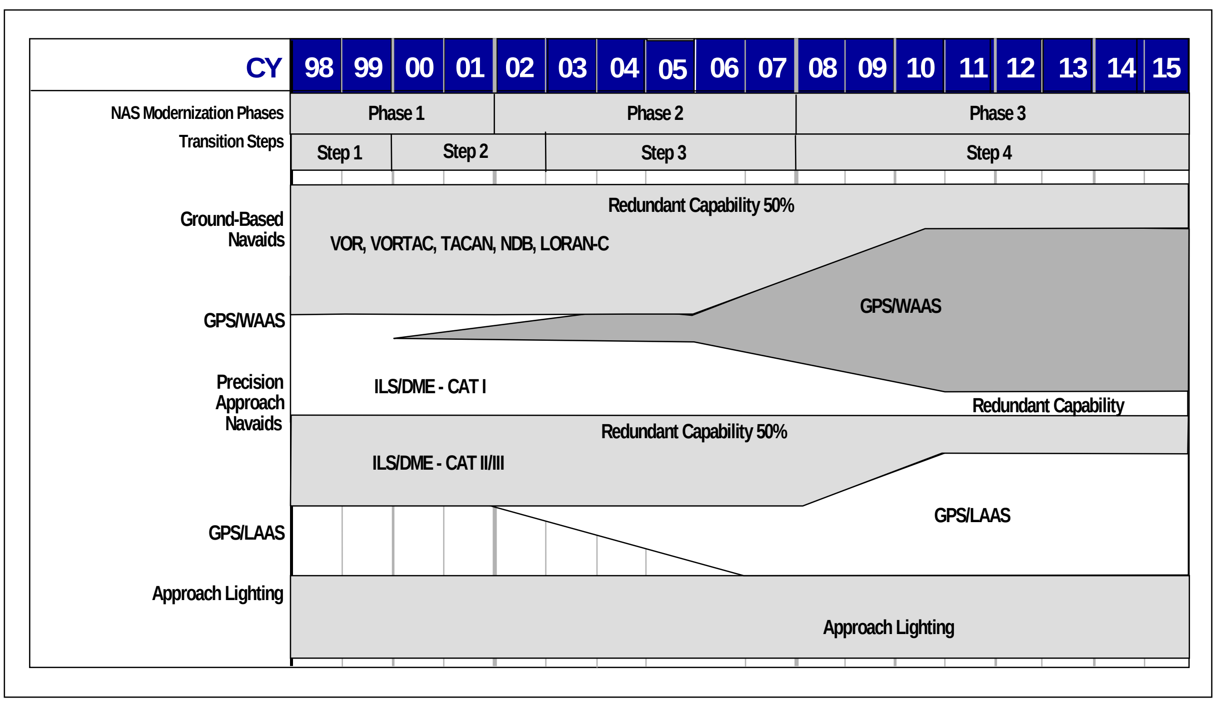

Figure 15-8. Navigation and Landing Transition

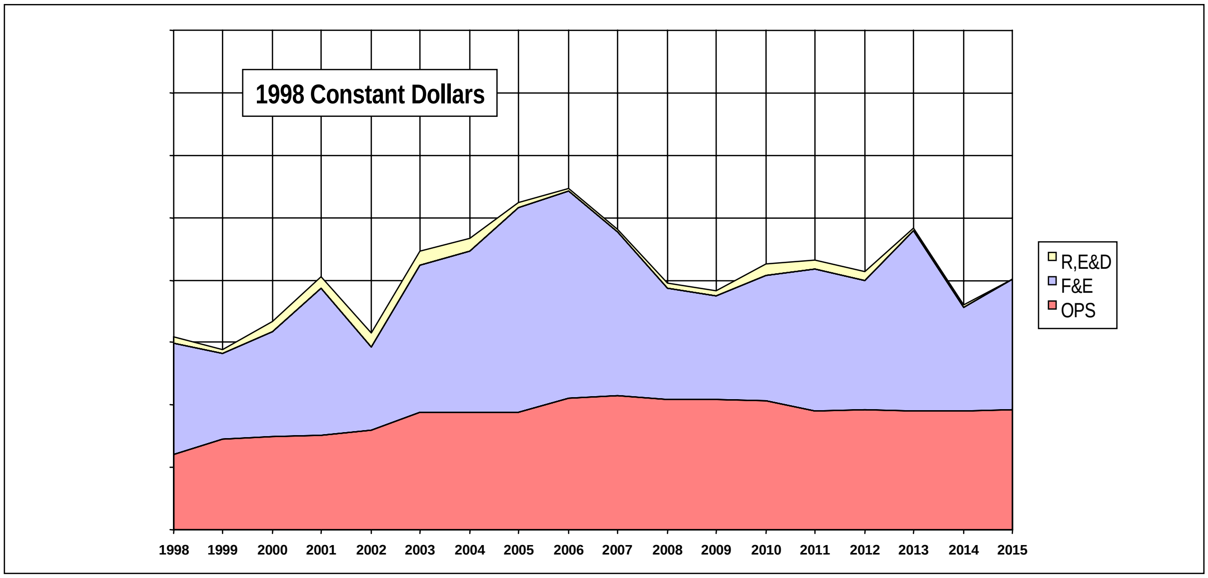

Figure 15-9. Estimated Navigation Costs

- Policies on carrying redundant equipage
- Programmatic issues
  - WAAS performance
  - LAAS/WAAS schedule
  - Development of LAAS standards
  - Second civil frequency
- Policy issues:
  - Notice of proposed rulemaking for airspace minimum avionics equipage and required navigation performance
  - Reuse of frequency spectrum presently dedicated to navigation for other aeronautical services
  - Continuation or shutdown of nonfederal Navaids
  - Rate and willingness of users to equip with WAAS/LAAS avionics
- International interoperability:
  - International agreements and standards for satellite-based systems to ensure global interoperability[9]
  - Operational procedures.

9. The United States leads or actively participates on several ICAO Air Navigation Commission (ANC) panels. Panel members develop international standards, which are approved by the Council, ICAO's governing body. It is essential to NAS architecture development to fully incorporate these international standards. Within the navigation area, recent standardizing efforts include work on: airspace planning methodology for determining separation minima by the Review of the General Concept of Separation Panel (RGCSP); standards and recommended practices (SARPs) development by the All Weather Operations Panel (AWOP); and long-term requirements and SARPs developed by the Global Navigation Satellite System Panel (GNSSP).

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