

Wide Area Augmentation System

# **Independent Review Board**

## **Report**

*January 18, 2001*



This report documents the findings of an Independent Review Board (IRB) for the Wide Area Augmentation System (WAAS). The IRB is administered by the Institute for Defense Analyses (IDA), under tasking received from the Federal Aviation Administration (FAA) on June 16, 2000, to review current activities and provide long term advice to the FAA regarding WAAS. The IRB reports its results directly to the Administrator of the FAA.

*The opinions expressed in this report are those of the members of the board and do not necessarily reflect official positions of the FAA.*

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## Outline

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This report follows the outline shown above.

First the *membership* of the Independent Review Board (IRB), its charter, and the meeting dates are summarized. Second, the *background* regarding GPS and current positioning capability is discussed.

Then we provide *overarching comments* regarding the FAA's WAAS program.

In October the board presented its *initial findings and recommendations* to the FAA Administrator, Ms. Jane Garvey. These are briefly reviewed. We believe those initial findings and recommendations are still valid and are incorporated in the overall final report.

Next we summarize the IRB's *expanded findings and recommendations*. This section is divided into two parts. The first deals with the *short-term activities* which lead to an initial operational capability.

In the second, we discuss the *longer term activities* which provide improved coverage and improved accuracy. This second group of recommendations also addresses the long-term goal of achieving a GPS based Landing System (GLS) with accuracy equivalent to that of the currently used Category I Instrument Landing System (ILS CAT 1). A summary of all recommendations is found in Appendix A.

The IRB provides views on WAAS Strategy in the next section.

Finally there is an overall summary followed by the Appendices.

## **IRB Members**

- *Mr. John Darrah* *Prior Chief Scientist AF Space Command*
- *Mr. William Delaney* *Defense Science Board - MIT/Lincoln Lab*
- *Dr. Paul Drouilhet* *Assistant Director Emeritus, MIT/Lincoln Lab*
- *Dr. John Hansman* *MIT Department of Aeronautics & Astronautics*
- *Mr. David Kellogg* *President, Solers*
- *Dr. Gene H. McCall* *Chairman GANS - Chief Scientist AF Space Cmd*
- *Dr. Pratap Misra* *MIT/Lincoln Lab*
- *Dr. Bradford Parkinson* *Stanford U., Prior CEO Trimble NAV, IRB Chairman*
- *Dr. Ben Peterson* *Prior Coast Guard Academy Eng. Dept. Head*
- *Dr. Alan Pue* *Johns Hopkins University*
- *Mr. Thomas Stansell* *Stansell-Consulting - Prior Leica*
- *Dr. James Spilker* *Stanford Univ. - Prior CEO Stanford Telecon*
- *Dr. Edwin Stear* *Prior Corporate VP Technology Boeing*
- *Mr. James Doherty* *IDA - Prior Commander Coast Guard NAVCEN*
- *Mr. L. Kirk Lewis* *IDA, Executive Director GPS IRT*

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The IRB members comprise a strong team, consisting of individuals with experience in GPS, aviation safety, navigation systems, software development, and deployment of complex systems. They represent well over 100 years of experience with GPS and related systems.

They come from government, industry, and academia. They are both independent and dedicated to improving service in the national airspace system.

## ***IRB Charter***

- **Review interim work products developed by the FAA's WAAS Integrity and Performance Panel (WIPP).**
- **Provide technical & strategic recommendations regarding the WAAS program.**
- **Assess other tasks as assigned.**

**In developing this report, the IRB held 9 plenary meetings, approximately 15 days in aggregate, plus numerous individual research sessions between August 3 and December 20, 2000.**

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The charter for the IRB is:

- **To review interim work products developed by the FAA's WAAS Integrity and Performance Panel (WIPP). Included are comments on adequacy and probability of successful system implementation for the initial deployment of WAAS.**
- **To provide the long-term technical and strategic recommendations regarding the WAAS program. Major actions that will lead to full operational capability (Cat I equivalent performance) are included.**
- **To provide other assistance and comments as appropriate.**

This report was developed during an intense period of meetings from August to December 2000. The *9 formal meetings spanned 15 full days*, and were supplemented with individuals or subgroups visiting various key facilities around the US. The meeting schedule is provided as Appendix B.

## ***Background***

- **GPS expanding Capability and Coverage**
  - *Two New Civil Signals (L2 and L5)*
  - *Improved Signal Structure (L5)*
- **National Augmentations (NDGPS, WAAS, LAAS)**
- **Deliberate degradation (S/A) Off**
  - *WAAS still needed for certification of Integrity*
- **Eleventh hour crisis in Development and Fielding of WAAS, a US system with world-wide implications:**
  - **Led to establishment of WIPP** (WAAS Integrity and Performance Panel)
  - **IRB also formed for independent oversight**

**January 18, 2001**

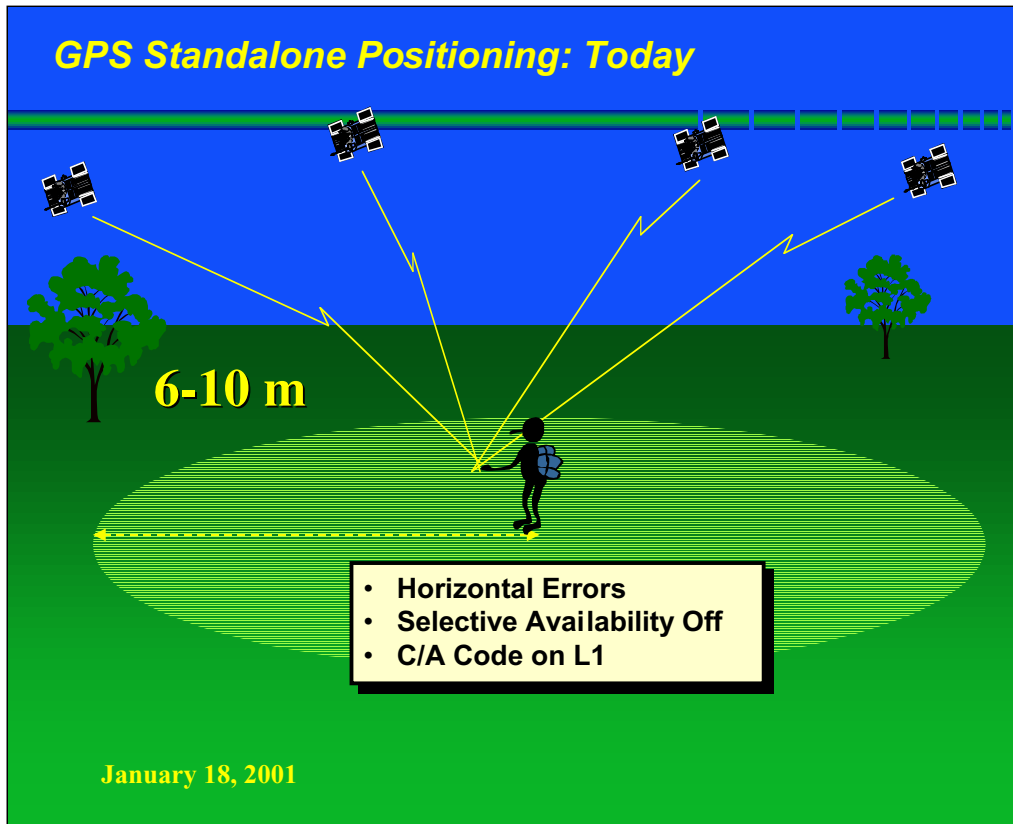
GPS has been operational since *December of 1994*. In the intervening years the number of users has increased to *over 15 million*. Since 1974, only one civil signal has been provided, which limits accuracy and robustness of the GPS service. In the last two years, a decision was made to provide *two additional, new civil GPS signals* one at L2 (1227 MHz) and another signal, called L5 (1176 MHz). L5, which will be the third civil signal, will have much greater capability than the existing civil signal at L1.

Recently, there have also been a number of new *national augmentations* to GPS including the Nationwide Differential GPS (NDGPS) service provided by the U.S. Coast Guard and the FAA's WAAS and Local Area Augmentation System (LAAS).

Although the Department of Defense (DoD) has now turned off the deliberate degradation of GPS (known as Selective Availability or S/A), the need for assured integrity for precision air operations is still a valid and essential requirement. *This requirement fully justifies the need for WAAS.*

Over the last several years the FAA has been developing WAAS. Unfortunately the system was late in achieving initial operation. The FAA then decided to establish a panel to address the technical impediments to fielding the system. This is called the WIPP. WIPP is composed of technical expertise from throughout the United States including members from FAA and the WAAS contractor (Raytheon). Shortly after establishing the WIPP, an Independent Review Board (IRB) was formed to provide the FAA Administrator an assessment of the WIPP's recommendations and the corrective actions being undertaken. Also requested was advice on future directions for the system.

**This is a unanimous report developed by the IRB.**

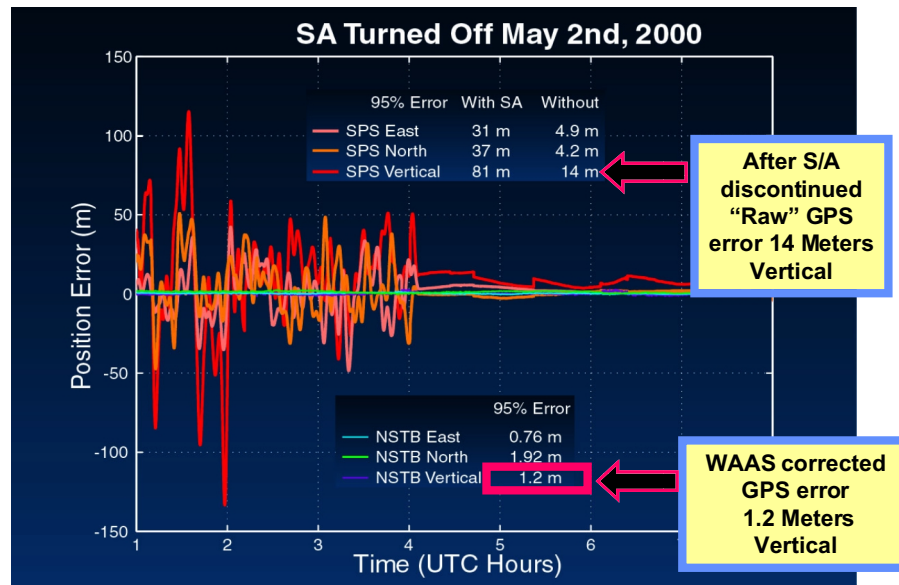


Illustrated here is typical *GPS worldwide accuracy which is 6 to 10 m horizontally*. This assumes the civil user is receiving the *L1 signal only*. Prior to discontinuing selective availability (S/A) the accuracy was typically five to eight times worse.

While this accuracy is acceptable for many flying operations, accuracy is not the main issue for aviation. Rather, it is creating a *bound on inaccuracy* that must be used to assure integrity for the flying user.

The FAA's WAAS is designed to provide that bound (or *protection limit*) to create the required level of integrity at every point within the WAAS service volume.

## Selective Availability Impact



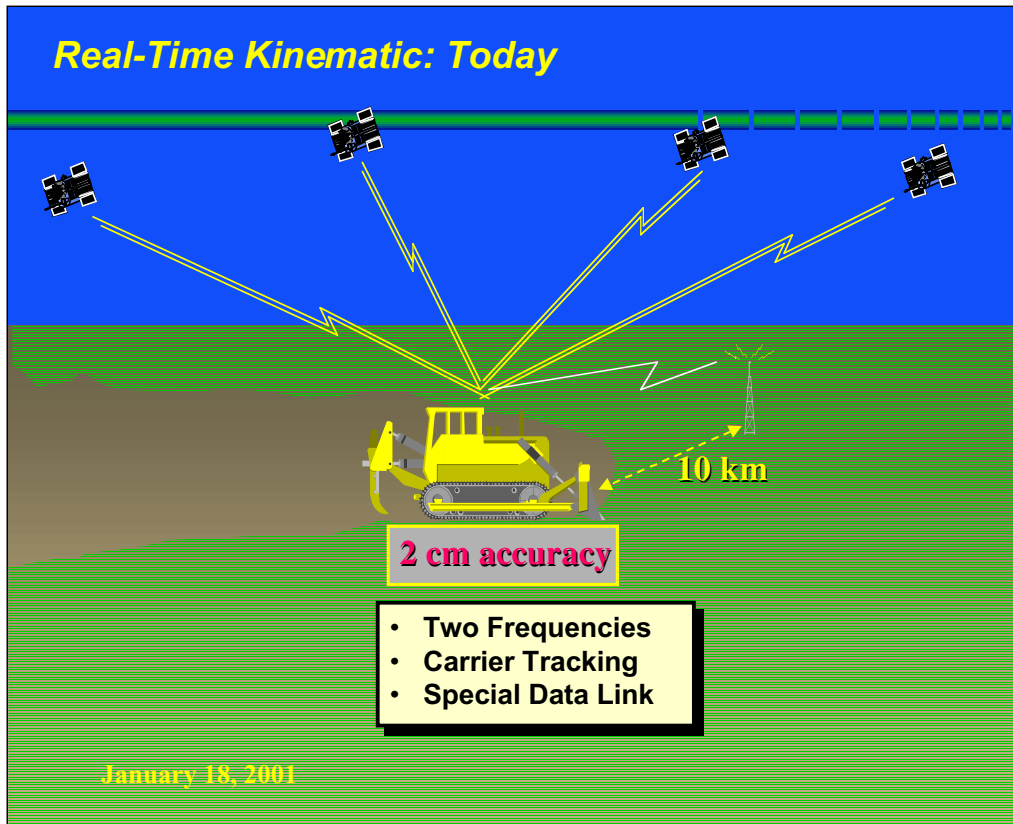
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No impact on WAAS accuracy

Shown is the actual positioning error during the period that S/A was turned off in May 2000. The vertical accuracy of WAAS-corrected GPS (1.2 m - one sigma) was unchanged whether S/A was turned on or not. Note this is for typical operations in the interior regions of the US.

While the WAAS-corrected accuracy is not affected by discontinuing S/A, the required bandwidth to transmit the WAAS corrections is much less since it has been discontinued. This may lead to more efficient operation of WAAS.

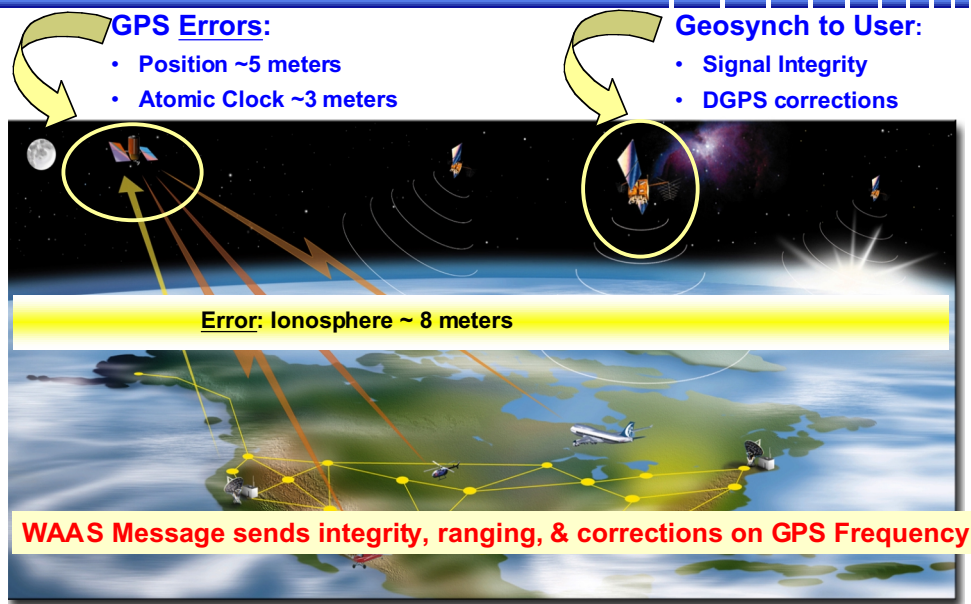




Using special differential techniques, the sophisticated civil GPS user can attain accuracies of 2 cm or better over a range of 10 kilometers to a calibrating reference station. To do this the civil user must use 2 frequencies and a special data link.

Although FAA's LAAS does not use these sophisticated RTK techniques, LAAS is in fact a local area system, and most LAAS users must be within line-of sight of the LAAS correction data link transmitter. When using LAAS, aviation users usually obtain greater accuracy due to their proximity to the reference station. In comparing WAAS and LAAS, the IRB felt there are mutually beneficial relationships between these aviation systems that should be exploited as the FAA moves forward. Appendix G further explains the synergies among WAAS, LAAS, and other national assets.

## Wide Area Augmentation System (WAAS)



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The **WAAS** concept is a **differential GPS system** designed to operate over a very large geographic region (virtually all of the US).

The WAAS system has *two basic purposes*. The first is to provide an *integrity message* which tells the user whether *ranging signals* from particular GPS or GEO satellites *can be included* in the navigation solution. The second purpose is to provide *differential corrections* that the user applies to the ranging measurements, allowing the user to calculate a *more accurate positioning solution*.

The major GPS errors are associated with the positioning of the satellite (an uncertainty of about 5 m), the atomic-clock's timing signal (an uncertainty of about 3 m), and the error induced by the free electrons in the ionosphere (an uncertainty of about 8 m).

The WAAS system concept uses about two dozen reference stations, at carefully surveyed locations to directly measure the GPS errors and measure the current delays associated with the ionospheric blanket. These stations transmit the ranging errors to a central facility for processing and an assessment of integrity. A message to the user is formatted and sent to a geosynchronous satellite.

The message is then relayed to the GPS user **on exactly the same frequency as the GPS signal**. This greatly simplifies the user hardware, provides excellent regional coverage and (when properly implemented) also **provides an additional GPS ranging source to strengthen the accuracy and integrity of the solutions**.

The system concept has been extensively prototyped and demonstrated by Stanford University and the FAA's Tech Center as a part of the national satellite test bed (NSTB) program that has been sponsored by the FAA.

## Support for WAAS - SNUG

- **GPS Integrity - *improved public safety***
- **Nationwide Assured Vertical Accuracy**
  - *Expanded operations capability for business, regional, helicopter, and general aviation users*
  - *Precision approaches anywhere*
    - **Steady descent rate landings**
  - *Curved approaches, guided missed approach*
  - *Potentially tighter spacing in landing*

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As part of the IRB's review, testimony was requested from the **SNUG (Satellite Navigation Users Group)** which represents virtually every member of the aviation community. SNUG represents major air transport carriers as well as cargo, regional, business, general aviation, and helicopter users. It also includes representatives of DoD.

The SNUG specifically and unanimously endorsed WAAS as an important part of the future aviation infrastructure. SNUG representatives singled out the improvement in GPS integrity, particularly as it related to improved public safety.

An important part of this, the IRB was told, was the nationwide assured vertical accuracy which allowed expanded operations for a number of significant aviation users. For example, WAAS would provide precision approaches anywhere including steady descent rate landings; this they felt was an important addition to instrument approaches (for runways not equipped with ILS).

SNUG also pointed out the application of WAAS to both *curved approaches* and *precision guidance for missed approaches* (not possible with ILS), which should improve access and safety in mountainous areas or restricted urban environments.

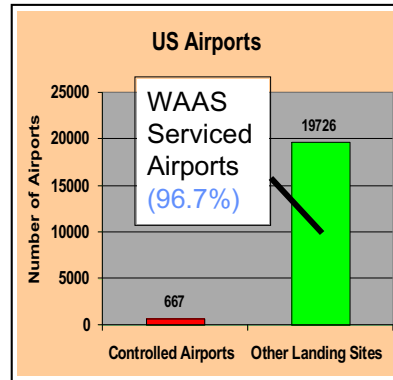
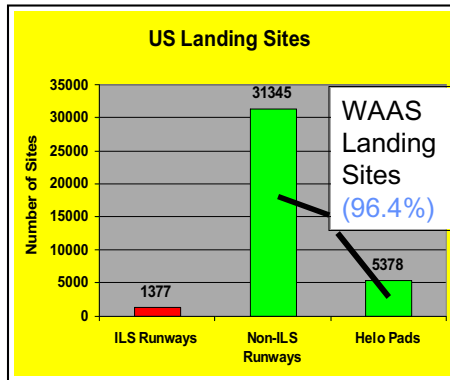
While tighter spacing of aircraft during landing is potentially possible, SNUG indicated that other issues must be resolved to make this a reality.

## Airports & Landing Sites Serviced by WAAS

### WAAS Enhances Safety at over 95% of US Facilities\*

[Particularly beneficial for Business, Commuter, Commercial, Humanitarian, Helicopter, and General Aviation]

\* Numbers from FAA Data



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This illustrates an example of a WAAS safety application, suggested by the SNUG.

As air travel and air freight continue to expand, pressure on the non-ILS facilities will increase. WAAS offers improvements in safety and integrity at over 95% of current US facilities, according to FAA data. While the large commercial airports will continue to use ILS or eventually LAAS, WAAS is a cost effective way to expand IFR operations and provide vertically guided approaches at the peripheral or feeder airports. Done properly, this may help relieve congestion at the larger commercial airports, possibly helping to arrest the significant growth in arrival delays.

Avionics manufacturers are anticipating the benefits of WAAS, and are developing 14 and 15 channel, WAAS-ready receivers. See Appendix K for details.

## Overarching Comments

- For NAS Modernization Plan
  - **WAAS must be a success**
    - **Cornerstone of SATNAV**
- Commissioned signals in space drive adoption - **Users follow**
- Benefit to the nation is
  - **Full SATNAV program for all users**

**SATNAV ENABLES NATIONAL AIRSPACE  
MODERNIZATION & PROVIDES WORLD  
LEADERSHIP IN AVIATION SAFETY**

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It is useful to provide some *overarching comments* regarding WAAS in the context of this review. It is the unanimous opinion of the IRB that WAAS must be a success if the FAA is to implement and achieve its National Airspace System (NAS) modernization plan. A cornerstone of that plan is the use of satellite navigation (SATNAV) for a number of essential aviation applications.

The history of SATNAV, including GPS and the Nationwide Differential GPS (NDGPS) service, has proven that the ranging signals must be available before the users will equip to use them. **In other words the signal in space must come first.** We unanimously believe that no significant equipage will occur until the users see that the FAA is serious in providing the WAAS service.

Having said that, it is useful to point out that **some users are already starting to benefit from WAAS.** The program office sees evidence of this when the contractor turns off the signal for upgrades; they receive numerous complaints from users ranging from farmers to selected aviation users. See Appendix E for early uses of WAAS.

The **benefit of WAAS** to the nation is not simply to the aviation community, as important as that may be, but to **all GPS users** since the WAAS signal will be incorporated into all future GPS sets- land, sea, and air- as soon as it is shown to be reliably available.

Thus we believe that satellite navigation with WAAS not only enables national airspace modernization but also acts as a concrete symbol of GPS world leadership in aviation safety.

**Initial Brief** (October 17, 2000)

- **WAAS concept sound - well supported by users**
- **Works better than current integrity approach can prove**
  - *but will be OK for LNAV/VNAV*
- **LNAV/VNAV is only an initial step on road to GLS**
  - *WAAS will evolve*
- **GEO single thread to failure**
- **No credible schedule**

**WAAS INTEGRITY & PERFORMANCE PANEL (WIPP) IS A SUCCESS**  
**- DE FACTO SYSTEM ENGINEERS**

January 18, 2001

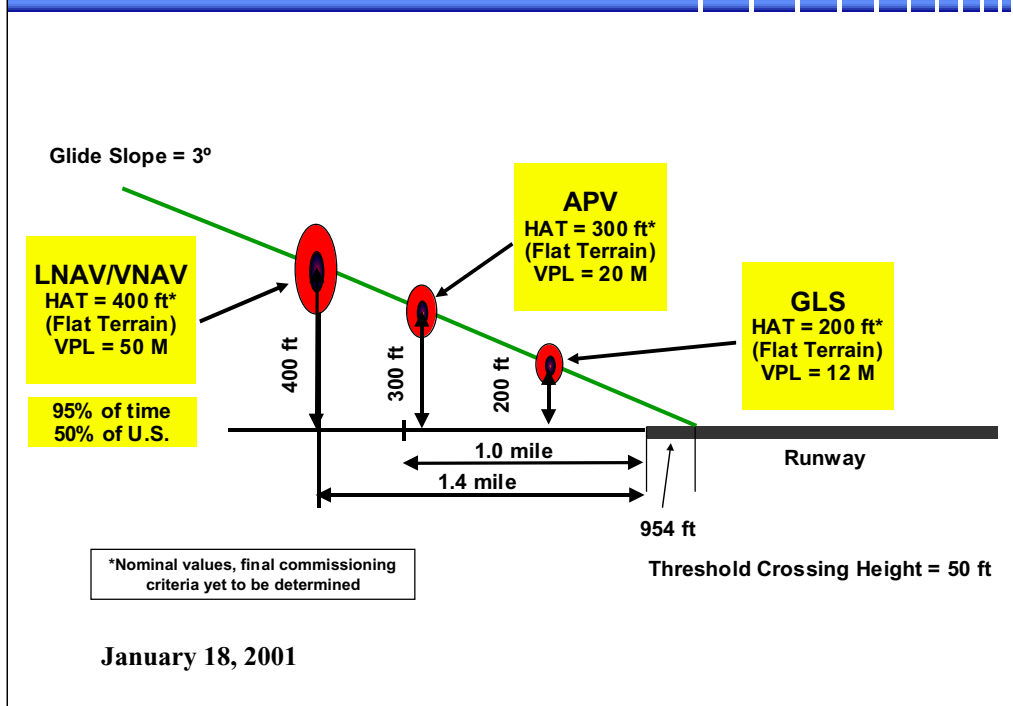
This summarizes the **IRB's interim findings**. We believe they remain valid and are therefore incorporated in this expanded report.

- **WAAS Concept Sound.** The IRB believes that the WAAS concept is technically sound as demonstrated by many millions of test data points provided to us by Stanford University and FAA Tech Center. In addition we found that the system was well supported by the most significant user groups.
- **WAAS Works Better Than Can Be Proven.** Surprisingly the WAAS system works better by a factor at least two than the current approach to calculating integrity can actually prove. However, even given this handicap, the system is nevertheless expected to be satisfactory for LNAV/VNAV. This statement is further illustrated on the next chart. LNAV/VNAV is defined on a later chart.
- **Initial Capability Only the First Step.** As will be discussed, the LNAV/VNAV milestone is only an initial step on the road to a GPS landing system (GLS). We believe there are affordable improvements that will allow upgrades to WAAS that will be very cost-effective to the aviation community.
- **Single Coverage GEOs.** Because of the current reliance on only two geosynchronous satellites for transmitting integrity and correction messages, it remains clear to the IRB that WAAS is a single failure away from reducing coverage by about 50 percent.
- **No Credible Schedule.** At the time of the initial brief we were not provided any credible schedule for the completion of the initial phase of WAAS. This was understandable at the time because certain critical requirements had not been defined. Please see later comments in this report.

The **WAAS Integrity and Performance Panel (WIPP)** is a success and has been **acting as the de facto system engineers** for the WAAS development.



## Definitions & Capability of Approach Levels



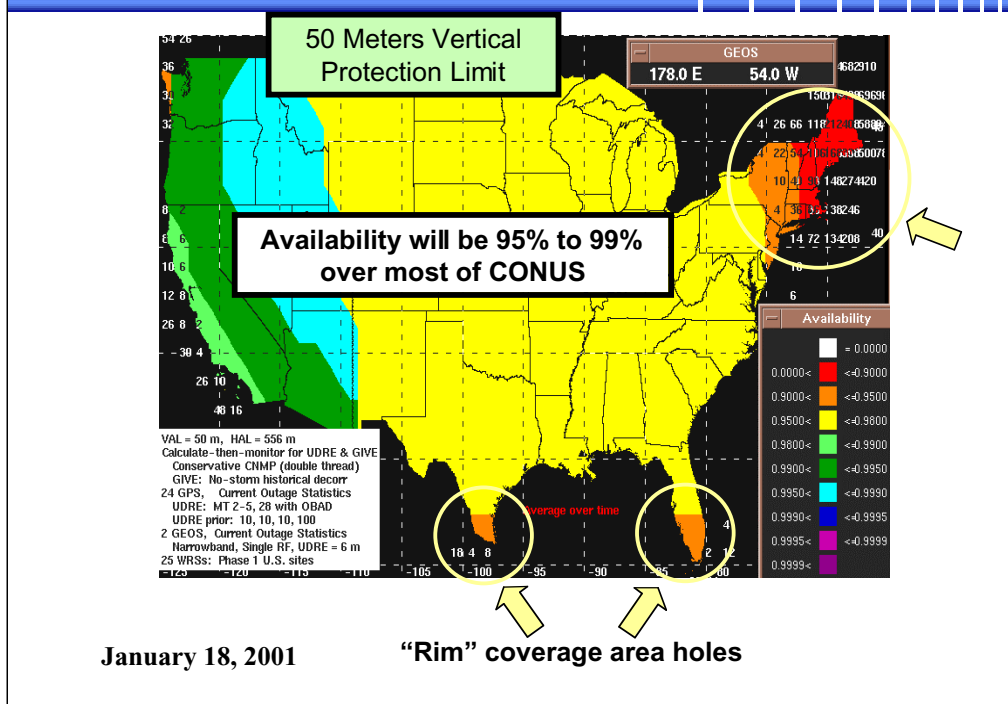
It is important to understand the definitions of the initial operational capability, called LNAV/VNAV. This first phase of deployment will provide a Vertical Protection Limit (VPL) of 50 meters or better, more than 95% of the time over at least 50% of the conterminous US (CONUS). Current analysis and expectations for this phase are shown on the next chart. This analysis shows an initial capability with availability of 95% to 99% over most of the CONUS.

The initial LNAV/VNAV capability should allow *nominal* decision heights of 400 feet over most of the landing locations, depending on local obstacles and other factors. **Further descriptions of nominal capabilities for WAAS are shown below.** At the APV level of capability (requiring a VPL of 20 meters) the minimum height above touchdown is 300 ft which is within 1 mile of the runway threshold for a 3 degree glideslope. Note that 1 mile is the minimum required visibility for runways without approach lighting. The GLS level of capability has a minimum height above touchdown of 200 ft and requires a VPL of 12 meters. At the most improved WAAS levels of capability the governing factors may be terrain, visibility, and lighting rather than positioning accuracy.

WAAS Capability	VPL	HAT	Visibility	Terrain	Suppl. Lighting	Decision Height
LNAV/VNAV	50m	400	1 Mile	Flat	No	400
APV	20m	300	1 Mile	Flat	No	300
GLS	12m	200	? Mile	Flat	Yes	200



## LNAV/VNAV Availability and Coverage (no significant satellite failures nominal ionosphere)



The IRB requested a careful simulation of WAAS availability over the CONUS and Alaska and Hawaii. This availability was evaluated for different system level accuracies. The results for the initial commissioning of LNAV/VNAV of the system under nominal conditions over CONUS are shown here. The GEO constellation has only two satellites, and **both are assumed to be working**. The additional assumptions for this particular simulation are shown in this small box in the lower left corner.

The availability over most of the CONUS is expected to range from 95 to 99.9 percent (as shown by the yellow, green and blue colors). Notice that the rim areas of the CONUS suffer from a lack of reference station coverage. The IRB reviewed means of improving this "rim" coverage, which are discussed later in this report and in Appendix F.

**Even without additional reference stations, the availability as shown in this chart meets the system requirements for LNAV/VNAV as described to the IRB.**

## ***Findings – Near Term***

- **FAA's establishment of WIPP was essential to completing WAAS**
  - *limited in scope*
  - *performing system engineering function*
  - *defining commissioning criteria - some work remains.*
  
- **WAAS has yet to produce a credible schedule**
  
- **WAAS works better than current integrity approach can prove**
  - *will be OK for LNAV/VNAV*

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### **Findings near term.**

• **WIPP.** The FAA's establishment of WIPP was a creative and essential step to complete WAAS. The WIPP is currently limited in scope to those near-term technical issues that have delayed the initial the deployment of the system.

As a part of their activity, the WIPP has been performing the critical system engineering function for WAAS. This has provided detailed trade-offs and optimization studies for the design and deployment of the overall system. WIPP achieved a major milestone in December when all system algorithms completed their definition and acceptance phase; that is, under WIPP leadership, the contractor completed the algorithm description documents (ADD) for LNAV/VNAV, and these were approved by FAA.. WIPP has also worked closely with the FAA's certification authorities to complete the definition of commissioning criteria to include safety cases and test success criteria. While this is not yet completed they believe that all major issues should be resolved no later than the first quarter of calendar year 2001.

• **Schedule.** As reported in October, the IRB can still not find a credible schedule. However, we believe there is good promise that a firm schedule can be provided in the March 2001 timeframe after the major remaining issues associated with certification have been resolved. WIPP has developed a near term work plan to finalize remaining process elements causing schedule uncertainty and to assess risk areas in the development process against which schedule slack should be apportioned. At the December 2000 IRB meeting, WIPP members reported that their goal is to have a credible schedule when the major issues are resolved in first quarter, calendar year 2001.

• **Accuracy vs Integrity.** Again, as reported in October, the IRB still finds that WAAS is providing much better accuracy, by a factor of at least 2, than the current integrity approach can prove. However, continued IRB review finds that the current integrity approach will enable WAAS to achieve LNAV/VNAV performance levels.

## ***Findings – Near Term (cont)***

- **Organization**
  - *dependent on a few critical people who are tired and a little discouraged*
  - *difficult lines of authority - see Appendix C*
  - *perception by workers that whole chain of command is not fully committed and engaged*
- **Budget inadequate & inadequately supported**

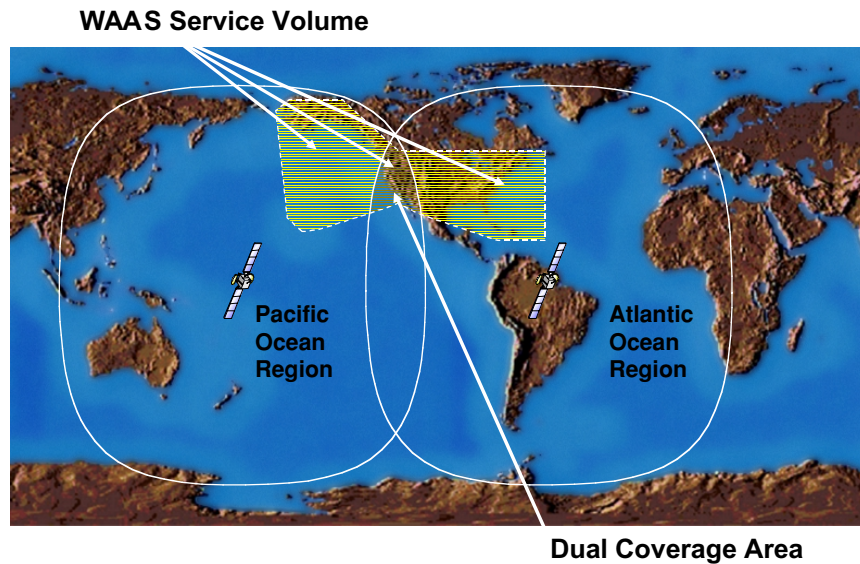
**If supported, and team stays intact, LNAV/VNAV with  $10^{-7}$  integrity should be attainable by 2003 with acceptable schedule risk.**

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### **Findings near term (cont).**

- **Organization.** The FAA's WAAS program is buried deep within FAA. This is documented in Appendix C. Also, the IRB found that the organization developing WAAS is perilously dependent on a few critical people. In many cases these individuals have been working very long hours and feel under-appreciated and appear to be somewhat discouraged. The situation is made more difficult by the confusing and long lines of authority. In addition there is a perception by the workers that the leadership at several levels within the FAA is neither fully committed nor fully engaged for success in this major program. Naturally this does not reinforce or strengthen the morale of the organization.
- **Budget.** For a variety of reasons the budget for the WAAS has not been adequately supported. For example the request for funds for additional geosynchronous satellite resources was not supported by Department of Transportation. While the program has clearly run into development difficulties, by and large the fundamental problem has been undue schedule optimism on the part of the original program staff. A realistic assessment of development time for a system of this complexity was apparently not made.
- **Summary.** The IRB believes that attaining LNAV/VNAV with  $10^{-7}$  integrity risk should be achievable by the year 2003 with acceptable schedule risk. However two necessary conditions are that: the system is strongly supported by the FAA, and the core team (FAA program office, Raytheon, and WIPP) stays intact through system delivery.

## ***Finding: WAAS GEOs are Single Thread to Failure***



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As depicted in this chart, the coverage of the two existing geosynchronous satellites (GEO) is required to cover the WAAS service volume; there is almost no overlap. One is over the Pacific Ocean and the second over the Atlantic Ocean. Clearly if either one of the satellites were to fail, coverage would be seriously reduced.

As FAA moves to full operation of WAAS, critical dependency on the geosynchronous communication link demands that the nation have prudent levels of redundancy to maintain close to 100 percent system availability throughout the WAAS service volume.

Optimal number and location of satellites is an issue that has been recognized by all those who have seriously studied WAAS. Various availability trade studies have shown that the optimal number of GEOs for the eventual system is four. The IRB believes that this is a correct conclusion.

**But as discussed in the near term recommendations, the IRB also believes that at least one more GEO is needed as soon as possible.**

See Appendix H for further discussion of GEOs.

## **Major Recommended Actions - Near Term**

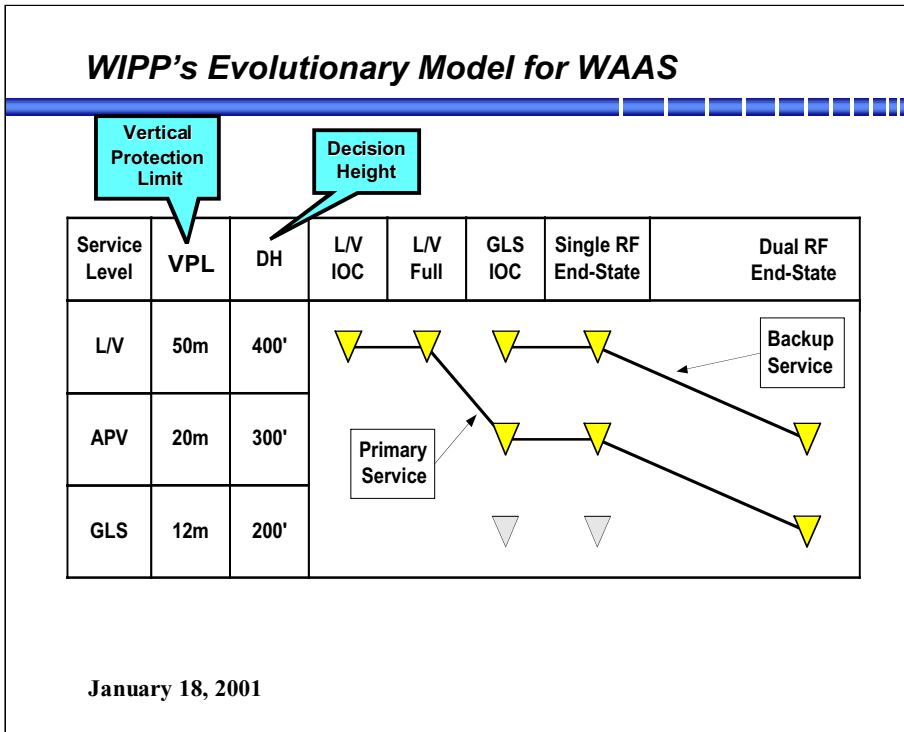
- **LNAV/VNAV Phase** [goal: attain VPL = 50 Meters]
  - **Define, coordinate, and freeze LNAV/VNAV commissioning criteria – Feb 2001**
  - **Solidify schedule – Mar 2001**
  - **Streamline reporting chain for WAAS and obtain full support of all FAA participants**
  - **Incentivize key individuals & organizations**
    - Boost team morale
    - Deliver critical resources
  - **Retain WIPP at least thru commissioning**
  - **Publicize the national payoffs from WAAS**
  - **Add one “bent-pipe” GEO**

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The IRB recommended actions are broken into three phases which relate to the attainment of certain performance capabilities of WAAS; the first is to attain LNAV/VNAV [VPL = 50 meters], called Near Term.

### **Recommended Actions Near Term**

- **Define Commissioning Criteria.** Take all necessary steps to define, coordinate, and freeze the LNAV/VNAV commissioning criteria **by February 2001**.
- **Solidify Schedule.** With commissioning criteria defined, solidify, **by March 2001**, the FAA schedule for delivery of LNAV/VNAV service from WAAS.
- **Streamline Reporting Chain.** Currently, the WAAS program, with high national visibility, is buried deeply in the FAA's organizational structure. The three key Associate Administrators are nominally supportive, but there appear to be long chains of command in each structure that make the fielding of this system unnecessarily difficult. This should be streamlined.
- **Incentivize the Team.** The FAA should take steps to incentivize key individuals and organizations both inside and outside the government who are working on WAAS. This should help boost the team morale, remove motivation for untimely departure, and provide greater assurance that the schedule can be met.
- **Retain WIPP.** The WIPP should be formalized as a part of the development team and continue at least through the commissioning of the Near Term effort. Some responsibility for cost and schedule should be included in a new WIPP charter. See Appendix D about the future role for WIPP.
- **Publicize the Total National Value of WAAS.** *WAAS is needed and justified by aviation requirements*, but there is potential for national payoffs which exceed those for the FAA. While the FAA's technical and safety requirements are the most stringent, benefits to others are very noteworthy. A significant effort should be undertaken to advertise total national benefits from this new capability. Similar to GPS experience since the 1970s, WAAS will provide benefits well beyond current expectations.
- **Immediately Add One “Bent-Pipe” GEO.** As was strongly recommended in the interim report of the IRB, it is essential that at least one additional bent pipe GEO be added to the initial phase of WAAS. Eventually we expect the GEOs will be autonomous (navigation package) payload types. In the near term the program is too dependent on a single-thread integrity link and also requires the coverage improvement of an additional GEO. See Appendix H for elaboration.



The latter part of this report is structured around the WIPP's model of an evolutionary path for WAAS. This is presented here. This evolution was developed and studied in depth by the WIPP. IRB believes that it is an appropriate, cost-effective, and feasible evolutionary approach for the later stages of WAAS. The actions and payoffs for this are further described in Appendix F.

Each phase is defined by the service level as shown by the Vertical Protection Limit or VPL ( which has also been referred to as vertical alarm limit, VAL). A given VPL essentially sets a decision height for final approach. In the final phase (GLS), WAAS will provide an approach accuracy that is equivalent to the current ILS CAT I. This chart shows the evolution from the initial WAAS capability (LNAV/VNAV, or L/V as abbreviated here) to the final capability (GLS). The *expected* capability is shown as the *primary service*. **In the event of various resources not being available the service would gracefully degrade to the *backup service*.**

As service levels evolve to the improved capability, the decision height for a landing aircraft should significantly decrease. Studies reviewed by the IRB showed that the goal of a GLS 200 ft decision height is desirable; however, they also show that **reducing the decision height from 400 ft to 300 ft has significant economic payoff for the general aviation community**. This level of capability is referred to as Approach with Precision Vertical guidance (APV).

Depending on resources, FAA support, and the availability of GEOs, there *would be roughly two years between each successive capability* as shown on this chart. Again, see appendix F. There is also some hope that a second frequency signal would be available earlier which would greatly aid in accelerating this schedule. See Appendix I on Dual Frequency Avionics.

The following findings and recommendations relate to the the second part of this evolutionary plan: the path from LNAV/VNAV to APV and ultimately GLS capability.

## Findings – Later Phases

- **Reference stations and antennas are poorly sited which limits system accuracy**
- **Initial system architecture relies on uncertified corrections processor and receivers**
  - *Architecture patched, and complicated, with additional certified safety processor*
- **Actual test results (millions of data points) suggest that integrity calculations are conservative by at least a factor of 2**
- **Many opportunities exist for simplification and system performance improvements**

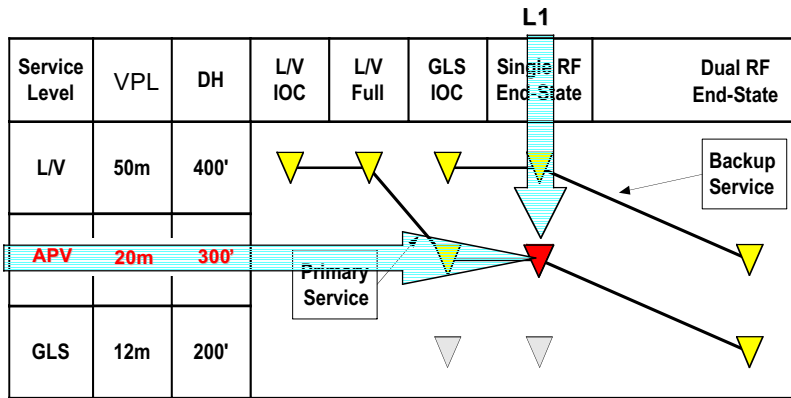
**WIPP has outlined a feasible evolutionary plan to attain single-frequency APV first, then GLS.**

January 18, 2001

The following **findings relate to the later phases of WAAS** (Phases as described on the previous chart):

- **Reference Stations.** The basic measurements of GPS ranging at many WAAS reference stations are unduly corrupted with *multipath and electro-magnetic interference* because of poor antenna siting. These noisy measurements are a fundamental limitation on accuracy for the whole system. Proper siting is not expensive but requires exercise of solid system engineering judgement. WAAS is safe, but non-optimal measurements lead to larger than necessary bounds on calculated worst-case inaccuracies.
- **Architecture.** The original decision to incorporate an uncertified correction processor has led to a very complicated overall system design in order to insure  $10^{-7}$  levels of integrity risk.
- **Test Measurements.** This was discussed on a previous chart. WAAS provides the parameters to each user to calculate a worst case (at  $10^{-7}$  probability) upper bound on inaccuracy after differential corrections are applied. This is called a *protection limit*. Actual prototype test data (many millions of data points) have shown that these limits are overly conservative (by a factor of at least 2) for operations not in the rim areas of coverage. This effectively (and unnecessarily) denies system use. (Briefings and IRB discussions made the point that *denial of WAAS use in itself could be a safety hazard since, for example, a helicopter in the fog or a user flying an approach in poor visibility would be denied access to the very instrument needed to successfully carry out these operations.*)
- **Improvements.** There are steps, suggested by the above findings, and reviewed by the IRB, which should simplify and improve system performance. An example is adding rim reference stations along US coasts as well as Mexico and Canada (with support from those governments) to supplement the WAAS network coverage. See Appendix G on Synergies.
- **The affordable, evolutionary plan advocated by WIPP is strongly endorsed in concept by the IRB as a cost-effective way to provide and evolve an essential National Asset for all GPS users.**

## WIPP Path to APV



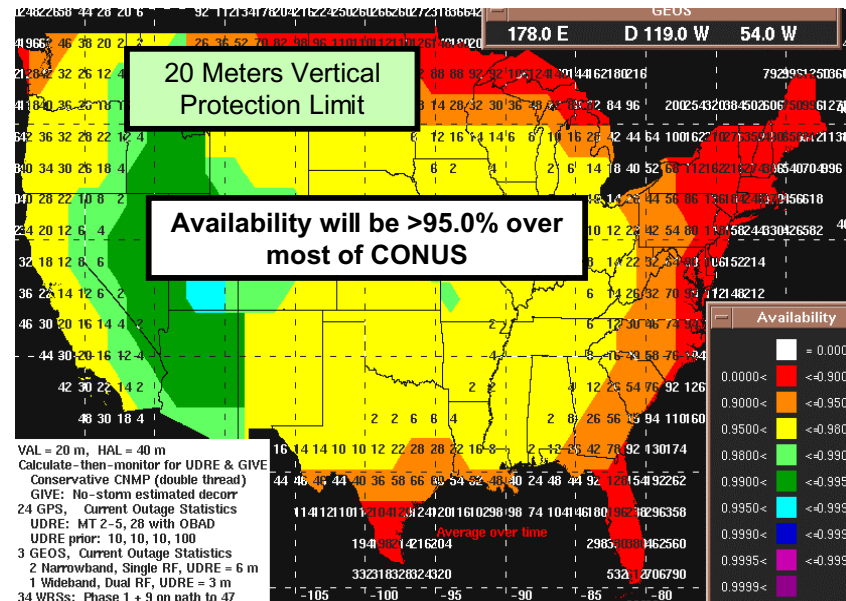
January 18, 2001

The next major step in the evolutionary plan for WAAS is to attain APV, defined to have a 20 meter Vertical Protection Limit (VPL). This would be for a single frequency user who must rely on WAAS for ionospheric corrections rather than directly measure the ionospheric error using two frequencies. This would allow a landing aircraft to fly down to about 300 feet over terrain, provided there are no local obstacles and appropriate landing aids have been installed. The resulting coverage is shown on the next chart.



## APV Availability and Coverage

(added 3rd GEO & no significant satellite failures - nominal Ionosphere)



This chart shows the coverage at a **Vertical Protection Limit of 20 meters** for CONUS when the APV is attained. The yellow of the central US indicates availability above 95.0%. Most of the mountain west, in two shades of green and blue, exceeds 98.0%. **Note the main reason for increased availability in the western mountains is the addition of the third GEO.**

The calculation assumes a **single frequency user** with a nominal 24 satellite GPS constellation (currently there are 27) and **3 Geosynchronous Satellites**, located at the longitudes shown in the upper right corner of the chart.

## ***Findings – Later Phases (cont)***

- **Early use of *second frequency* can eliminate major cause of conservatism (measure rather than model ionosphere)**
- **To attain a much more robust end-state WAAS, good system engineering demands three-signal *navigation packages* on GEOs**
- **Insufficient emphasis on performance *outside CONUS***

**There is a credible evolutionary path to GLS with 12 m VPL and  $10^{-7}$  integrity.**

January 18, 2001

Continuing the **IRB findings** for later phases:

• **Two Frequencies.** Use of two frequencies allow the user to directly measure the ionospheric delay which eliminates the major cause of conservatism in calculating the bounds on worst case errors (protection limits at  $10^{-7}$  probability). The upgraded GPS Block IIR satellites will broadcast a clear civil signal on L2 (1227 MHz), with first launch about 2003. While this is not a fully protected aeronautical frequency, it still should be adequate to provide periodic calibration of ionospheric delays. See Dual Frequency Avionics discussion in Appendix I.

• **Navigation Package Payloads on GEOS.** Careful studies show that the fully operational WAAS should include geosynchronous satellites with all three civil signals and on-board generation of these signals. (On board generation assures tight code/carrier coherence across all frequencies, fully compatible with GPS; see discussion of GEO Autonomous Navigation Package Payloads in Appendix H.) These fully capable ranging signals will be very valuable in assuring WAAS coverage and accuracy. This capability will also allow the ranging signal to increase LAAS availability (as well as be used by a host of commercial and civil users). Of particular interest is the added robustness for tracking airport vehicles which could cause fatal runway incursions. The high elevation of at least two GEOs is a major counter to the typical problem of low elevation satellite shading due to buildings and other aircraft on the ground.

• **Northern Coverage.** The IRB has not seen adequate emphasis on performance outside CONUS (e.g. Alaska). We have suggested that the WIPP give this increased attention.

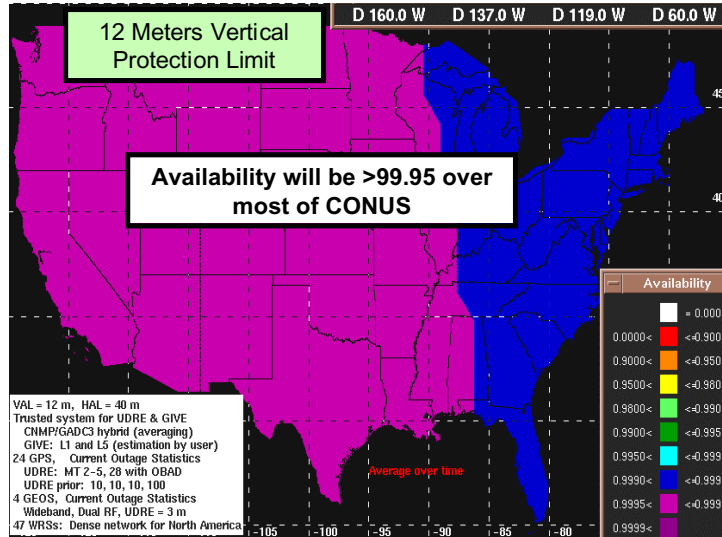
*The IRB finds there is a credible, affordable, evolutionary path to full GLS capability (dual frequency) with 12m vertical protection limits, excellent availability and coverage, and  $10^{-7}$  integrity risk.*



## GLS Availability and Coverage

(Dual Frequency User)

(no significant satellite failures, nominal Ionosphere)



January 18, 2001

The calculated availability over the CONUS for full 12 meter VPL will be greater than 99.95% when GLS is attained.

Dual frequency receivers are assumed, as well as nominal system performance. These results also assume full accuracy, three frequency navigation package payloads on four well placed GEOs, and about 50% increase in reference stations.

The purple area of the western US represents greater than 99.95% availability. The blue area in the East is also excellent at over 99.90% availability.

## Major Recommended Actions Later Phases

- **Mid-term: APV** [goal: attain VPL = 20 Meters]
  - Upgrade selected system components
  - Extend rim coverage of reference stations, consider other national resources
  - Refine algorithms based on additional data
- **Long-term: GLS** [goal: attain VPL = 12 Meters]
  - Upgrade to a Certified Processor asap
  - Prepare for second and third Civil Signals
    - Acquire 4 GEOs with full (3 signal) Nav payloads
    - Develop MOPS & UE for full 3-signal use

January 18, 2001

The IRB recommends the following actions for the *later phases of WAAS evolution*:

### **Recommended Actions Mid Term** (APV with VPL = 20 Meters)

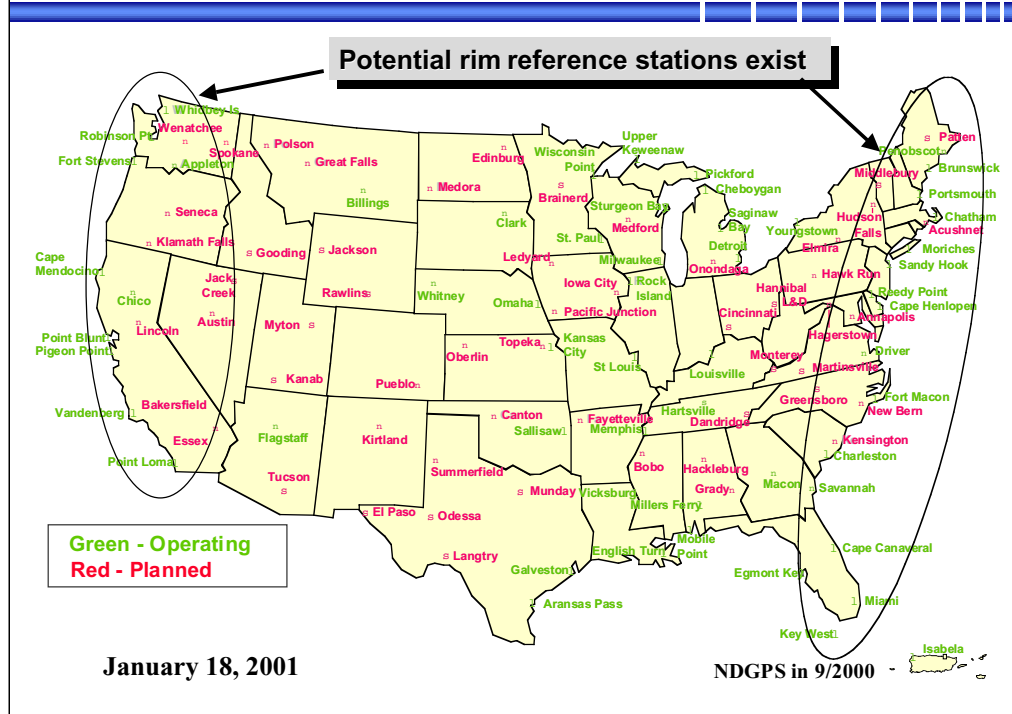
- **Upgrade Selected System Components.** A number of system components should be improved. This should not be very expensive but will have highly leveraged payoffs in performance and availability. The major items include certified reference stations, multipath-resistant antennas and siting, and dual/triple frequency reference receivers.
- **Extend Rim Reference Stations.** For very small cost, additional reference stations along the US coasts and in Canada and Mexico should be added. Existing national sites (such as NDGPS sites) should be considered, since they already have good antenna siting, access to communications and assured power, and are owned and maintained by Government agencies.
- **Refine the Calculations of Error Bounds.** As additional data on the ionosphere and other errors are gathered, a steady reduction in the conservatism of the error bound calculation should be possible. In turn this will lead to a more robust system with greater availability. In a related effort, the use of DRAIM (Differential Receiver Autonomous Integrity Monitoring) should be further explored, including the effect of additional GEO precision ranging sources. This is discussed in Appendix J.

### **Recommended Actions Long Term** (GLS with VPL = 12 Meters)

- **Upgrade to a faster Certified Processor.** Actions are already underway to do this. Also required is a migration to a single combined safety and corrections processor, with the attendant certified software, including simplified orbit calculation and smoothing.
- **Prepare for the Second and Third Civil Signals.** This should include several actions, at a minimum:
  - Acquire 4 GEOs with navigation package payloads (including fully synchronized L1, L2, and L5 signal capability).
  - Develop MOPS and prototype user equipment for full 3-signal use.

Anticipating the signals in space will speed the benefits to all national users. Further comments on the benefits of the evolution of WAAS are found in Appendix F.

## Nationwide DGPS - Synergy Opportunity



An example of an opportunity for synergism with existing national resources is shown here. These sites are the DOT sponsored and Coast Guard operated NDGPS service locations. Each site has (or will have) communications, assured power, and surveyed locations for GPS reference receivers.

While these two systems (WAAS and NDGPS) are complementary and serve somewhat different purposes, the idea is that a sharing of resources would greatly benefit the taxpayer.

Note that the existing NDGPS receivers are not directly usable. Although they are dual frequency and have external data ports, they do not use certified software and do not (yet) decode the WAAS signal. It is the location, power and communications that could possibly be shared. In particular there is extensive rim coverage in areas that would greatly benefit WAAS availability.

A similar opportunity for synergy exists with LAAS, which will be at all major airports as well as some smaller regional and business airports.

GPS and the National Imagery and Mapping Agency (NIMA) provide worldwide, secure, two-frequency monitoring of the GPS constellation. Data from these sites may be accessed for additional information, particularly about rising GPS satellites.

See discussion of Synergies in Appendix G.

## ***The IRB's Longer Term View of WAAS***

- **WAAS is a *foundation* of the FAA's National Airspace System (NAS) Modernization Plan**
- **WAAS is an *evolutionary program*- user value will continue to grow**
  - *Specific upgrades/improvements have been identified and recommended*
- **FAA's commitment to WIPP's plan for *evolutionary development* of WAAS should be firm**
  - *It is a relatively small incremental investment*  
[long range goal, Cat I or better 99.9% of the time]

**January 18, 2001**

The IRB has converged on a long-term, or strategic view of WAAS.

It is clear that WAAS is the cornerstone to the modernization of the National Airspace System.

We suspect that the true value of WAAS to aviation and to the nation is actually understated, as is common with a "new" system. Early WAAS use and then its first formal step, LNAV/VNAV commissioning, are important and very useful (including allowing the user community to gain confidence and familiarization). That said, there are a series of evolutionary steps, identified and advocated by the WIPP, and generally supported by this IRB, that will significantly increase the value over the next 5 to 10 years. See appendix F.

We have seen preliminary quantified economic benefits, but feel that the real issue is *vision and capability*. The users are already coming as evidenced by the complaints when the prototype WAAS is not available.

A necessary condition for the full benefits of WAAS to be realized is the ongoing FAA support and commitment to the evolutionary development program. *The long range goal, which the IRB believes achievable, is Category I type precision landing accuracies, 99.9% of the time over the entire WAAS operating volume.*

## Conclusions

- **WAAS concept is sound**
  - *WAAS users support system*
  - *WIPP has been remarkably successful*
  - *LNAV/VNAV defined, some steps remain*
- **An affordable, achievable, evolutionary path to full GLS has been identified**
- **Committed leadership is key to success**
  - *Particularly schedule definition and discipline-*
  - *Stable resources are essential (including additional GEOs)*
  - *Contractor must be incentivized to deliver LNAV/VNAV by December 2002*

January 18, 2001

### The IRB conclusions:

• **WAAS Concept.** Based on overwhelming evidence, the **WAAS concept is sound**. The prototype is working quite well. It was gratifying to hear of the strong user's support for the system. The FAA should be congratulated for conceiving and implementing the WIPP. **WIPP has been remarkably successful and should be continued as the WAAS system engineer.** See Appendix D. The definition of all critical certification issues and solutions should be completed in the first half of 2001. With appropriate support and program stability, the first phase (LNAV/VNAV) should be in place by early 2003.

• **Evolutionary Path.** The major evolutionary steps to full capability have been identified by the WIPP and confirmed by the IRB. This should lead to full GPS Landing System (GLS) capability. **WAAS is not competitive with, but very much complementary to, LAAS.** The synergies should be identified and used for the benefit of the flying public and the US taxpayers. Further thoughts are discussed under Synergies in Appendix G.

• **Committed Leadership.** Above all, the IRB believes that **fully committed leadership is the key to success**. This has many facets including commitment to a well defined schedule and the discipline to make it happen. It requires "buy-in" by all three Associate Administrators and their organizations. **It also requires reasonable stability in resources (both budget and people), especially support for the near term and final GEOs.** The Contractor should be strongly incentivized to deliver the full certified system at LNAV/VNAV levels of availability no later than December 2002.



***Bottom Line***

***National WAAS capability  
can be achieved ---***

***it requires FAA renewed leadership,  
action & commitment***

**Fielding WAAS will demonstrate  
continuing U.S. resolve and international  
leadership in aviation safety.**

January 18, 2001

**The bottom line of the Independent Review Board:**

- The WAAS national capability is a reasonable and achievable goal with enormous benefits for all GPS users.
- It will require renewed and ongoing FAA leadership, action, and commitment.

The deployment of WAAS will be a concrete symbol of the US intent to maintain an international leadership role in Satellite Navigation.



# ***Appendices***

**January 18, 2001**

## ***Appendices***

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- A. List of Recommendations**
- B. IRB Meeting Schedule**
- C. FAA WAAS Organization**
- D. Future Role for WIPP**
- E. Early Use of WAAS**
- F. Evolution of WAAS to Full Capability: Actions and Payoffs**
- G. WAAS Synergies with Other National Systems**
- H. WAAS GEO Opportunities: Satellite Acquisition and Capabilities**
- I. Dual Frequency Avionics**
- J. Differential RAIM (DRAIM)**
- K. WAAS Avionics Developments**

**January 18, 2001**

In addition to a list of the basic report's recommendations and information about the IRB's meeting schedule, these Appendices include issues that were studied by the IRB during the course of this task.

These (issues) appendices (C-K) discuss in brief the major elements in support of the basic report and its recommendations. In some cases, additional study would be warranted to determine the best course of action.

- **Near Term: LNAV/VNAV** [goal: attain VPL = 50 meters]
  - *Define, coordinate, and freeze LNAV/VNAV commissioning criteria – Feb 2001*
  - *Solidify schedule – Mar 2001*
  - *Streamline reporting chain for WAAS and obtain full support of all FAA participants*
  - *Incentivize key individuals & organizations*
    - *Boost team morale*
    - *Deliver critical resources*
  - *Retain WIPP at least thru commissioning*
  - *Publicize the national payoffs from WAAS*
  - *Add one “bent-pipe” GEO*
- **Mid-term: APV** [goal: attain VPL = 20 Meters]
  - *Upgrade selected system components*
  - *Extend rim coverage of reference stations, consider other national resources*
  - *Refine algorithms based on additional data*
- **Long-term: GLS** [goal: attain VPL = 12 Meters]
  - *Upgrade to a Certified Processor asap*
  - *Prepare for second and third Civil Signals*
    - *Acquire 4 GEOs with full (3 signal) Nav payloads*
    - *Develop MOPS & UE for full 3-signal use*

**January 18, 2001**

Recommendations of the basic report focus foremost on achieving commissioning of WAAS LNAV/VNAV capability as expeditiously as possible. Once this initial capability is in operation, the mid- and long term recommendations lead to incremental improvements in the operational performance capabilities of WAAS.

Some actions for mid- and long term recommendations should not be delayed; to do so might put in peril achieving greater WAAS capabilities.

- **August 3, 2000** IDA
- **August 30-31, 2000** IDA & DOT HQ
- **September 6, 2000** IDA
- **September 27-28, 2000** Raytheon
- **October 16, 2000** IDA
- **November 1-2, 2000** Stanford
- **November 14-15, 2000** IDA
- **November 28-29, 2000** IDA
- **December 19-20, 2000** IDA

January 18, 2001

The IRB activities have been very intense over a compressed period in response to the FAA's sense of urgency. The IRB met nine times for a total of about 15 days of sessions. During these meetings, the IRB invited technical and management experts from government, industry, and academia to brief on specific technical issues and participate in discussions.

A number of FAA staff members including Associate Administrators participated in several IRB meetings. In addition, FAA members of the Integrated Product Team for satellite navigation, as well as the contractor team from Raytheon, presented their views.

To further the IRB's understanding of the whole situation, a number of members of the IRB visited contractor facilities and met with engineers at the FAA's Technical Center in Atlantic City, New Jersey, the Coast Guard's Command & Control Engineering Center in Portsmouth, Virginia, and others.

A number of the IRB meetings were held at approximately the same time as the WPP meetings. A number of members of the IRB attended those meetings as well.

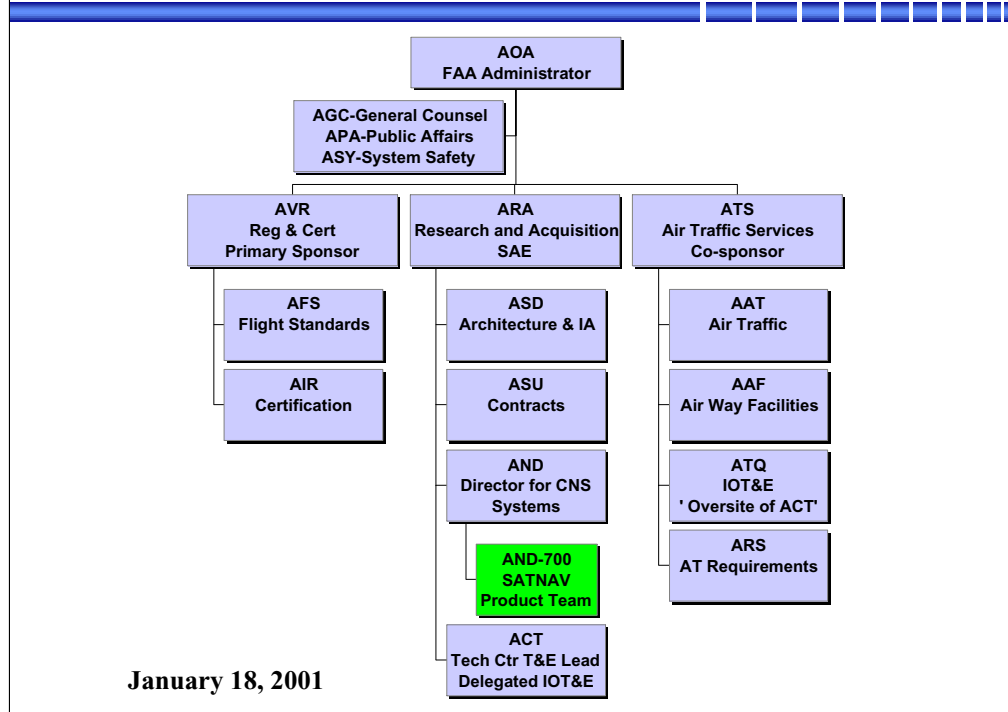
***FAA WAAS Organization***

**January 18, 2001**

As in many large Federal agencies, the FAA is made up of a complex and diverse set of organizations, staffs, and individuals. Some of these are dedicated to the WAAS program, and others are to varying degrees involved. To better understand how WAAS can be carried out within the FAA, the IRB diagrammed the organizational elements it perceived to be currently participating in WAAS.

# FAA Organizational Elements for SATNAV

C-2



The WAAS program office is part of the *Satellite Navigation (SATNAV) product team*, under the Associate Administrator for Research and Acquisition (ARA). This Associate is also the agency's Senior Acquisition Executive. The SATNAV product team includes the LAAS program and the program manager for international advocacy of SATNAV.

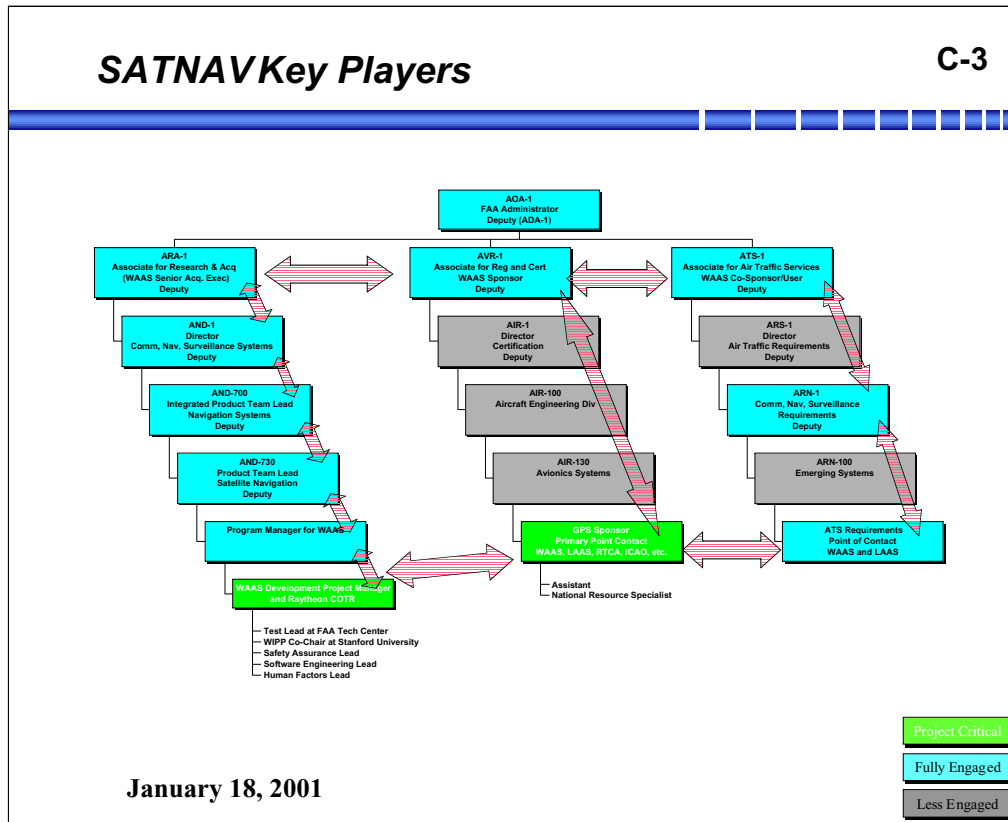
SATNAV is within the Office of the Director for Communications, Navigation, and Surveillance Systems. This Office is also acquiring other National Airspace System (NAS) Modernization elements, such as data link communications (NEXCOM) and Automated Dependent Surveillance (ADS-B). Within ARA, other offices provide NAS planning, contracting, and other support services; a particularly important organization is the FAA Technical Center, Atlantic City, NJ. FAA TC operates the National Satellite Test Bed (NSTB) and provides engineering guidance and support to WAAS and LAAS.

The sponsor for WAAS, LAAS, NEXCOM, and several other new systems is under the Associate Administrator for Regulation and Certification (AVR). This appears to be a change from the norm for ground based navigation systems, which have historically been sponsored under the Associate Administrator for Air Traffic Services (ATS). For example, ILS and air traffic control radar systems are sponsored by ATS. The AVR organization normally certifies systems developed outside the agency; for example, avionics manufacturers seek AVR's certification so that their equipment could be sold for use in aircraft. Nevertheless, AVR approves the WAAS acceptance criteria and sets the standards for commissioning WAAS LNAV/NAV capability.

The ATS organization is not uninvolved, however. It is the user organization that will both operate WAAS and maintain its components; both its Air Traffic Management and Airway Facilities Offices must accept the system from the program managers before WAAS can be placed in operations.

# SATNAV Key Players

C-3



This is the IRB's perception of *difficult lines of communications* within the WAAS program. These are observations, not judgements, but they collectively support the IRB finding about "difficult lines of communication."

The ARA organization is layered. *The COTR for the WAAS contract with Raytheon is fully seven layers below the FAA Administrator*, and the IRB observed key leaders/deputies at each layer to be interested and knowledgeable in WAAS issues.

The COTR's counterpart in AVR is at a similar level in the organization; the IRB did not see the same level of engagement at intermediate layers below the Associate and deputy.

The COTR's counterpart in ATS is also at a similar level; several layers were observed to monitor WAAS progress, particularly regarding future maintenance and upgrade requirements.

WIPP participants are at the COTR/equivalent level, and most day-to-day working decisions are made at this level. *The Associates meet together biweekly on WAAS for higher level issues and decisions.* The ARA organization uses a comprehensive project tracking system to focus Associates' efforts and for performance-based personnel management within ARA. During its integrity work over the past year, WIPP adopted a complementary project tracking and risk reporting system.

**Several individuals are absolutely key to the success of WAAS--to lose any of them would be a major setback to WAAS.** A lot of others are important--to lose one or two of them would hurt, but others could fill in.

The IRB recently learned of a proposed reorganization within the Navigation Integrated Product Team to address workload and lines of communication; we have not reviewed it.



***Future Role for WIPP***

**January 18, 2001**

The WAAS Integrity and Performance Panel (WIPP) was established in February 2000 to develop the LNAV/VNAV integrity solution and to define requirements for a long term GLS capability. *This initial planned work of the WIPP will be completed in January 2001.*

The IRB believes the WIPP has been very successful and moreover, has acted as de facto system engineers for the WAAS program. This coalition of contractor, FAA, expert advisors, and university researchers has been an effective means to identify and assess threat scenarios and candidate integrity algorithms to synthesize solutions.

The inclusion of recognized GPS experts provided oversight and advice of significant value to the WAAS program. Before the WIPP, there was an absence of independent reviewers and a deficiency in required system engineering that led, at least in part, to recent delays in WAAS commissioning.

The IRB also believes the role of the *WIPP should be expanded to encompass more complete system engineering functions* and related activities for the successful introduction of initial WAAS capability and then for evolutionary improvement of WAAS to precision approach capability. In addition to system engineering, *WIPP has been extremely valuable in focusing effective communication among groups critical to WAAS success, including the FAA acquisition program and sponsor, contractor, and outside experts.*

### WIPP is the de facto system engineer for integrity design

- **Within its limited tasking, WIPP is highly effective**
  - *Limited tasking; chartered for LNAV/VNAV & roadmap to GLS*
  - *Accepted current system design, components*
  - *Facilitated communications, focused engineering effort*
  - *Developed technical solutions for integrity*
  - *Scheduled to disband on completion of initial task*
  
- **Recommended future role; codify in new WIPP charter**
  - *Add new requirement - cost & schedule impacts*
  - *Widen scope - all engineering concerns*
  - *Provide flexibility to match new responsibility*

January 18, 2001

WIPP's charter in 2000 was limited to technical development of integrity algorithms to meet LNAV/VNAV initially. The WAAS architecture, including system, subsystem, and component breakdown, and interfaces, was taken as given. In developing its roadmap for evolution of WAAS performance to APV and GLS capability, WIPP began a deeper look into these initial constraints; some relaxation may significantly enhance the ability to achieve APV and GLS performance from WAAS. Although WIPP members appeared sensitive to cost and schedule impacts of their work, collectively WIPP focused strongly on technical issues.

WIPP also served to focus and facilitate communications among FAA, contractor and other personnel on the technical tasks. Since it is scheduled to disband, one consequence may be the loss of these direct lines of communication.

For the future, FAA should recognize that **the experience and knowledge gained by WIPP over the past year uniquely qualify WIPP to assume the system engineer role**. WIPP requires *an updated charter* that adds the requirement to consider cost and schedule, as well as technical, in its recommendations.

The new charter must also widen the scope of WIPP technical responsibility to all of WAAS, not just integrity considerations. And finally, *the charter must allow WIPP flexibility to consider subsystem, interface, and other changes in WAAS*.

- **WAAS requires specific technical expertise not currently found at FAA or contractor**
  - Contractor was not required to perform this function
  - FAA retained function but lacked capability
- **System engineer needed to**
  - Close on technical plan for program completion
  - Assess technical, schedule/cost, risk, performance trades
  - Focus effective communications among stakeholders
- **WIPP facilitated communications and bridged major FAA and contractor organizations**
  - Requirements generators/sponsors (AVR)
  - Design & development engineers (contractor)
  - System operators/users (ATS)
  - Program managers (ARA)

**WAAS System Engineering is required into the indefinite future.**

January 18, 2001

*Nobody in the FAA or in the contractor has been formally designated as the system engineer for WAAS. The IRB learned that the contractor was not required to perform this function, and the FAA had elected to retain it. Although we observed a number of persons and groups that performed some related functions, there was no one person or group that took charge. WIPP became the system engineers for integrity issues; because of the far reaching impact of integrity, WIPP made system engineer decisions about WAAS when needed.*

GPS/WAAS and associated navigation performance requirements involve integration of complex multidisciplinary concepts. WAAS integrity requires understanding the physics of the ionosphere, software development, computer operating systems, GPS receiver technologies, and other skills. Needed experience is found among few individuals and organizations.

Implementation of WAAS requires trades among many system components, algorithms, subsystem interconnections, and design choices.

During the past year, *WIPP has also proved its value in facilitating effective communications* among the key stakeholders in WAAS. These include FAA and Raytheon personnel: the sponsors in the FAA Verification and Certification organization, the program managers in FAA's Research and Acquisition organization, the customers who will eventually operate and maintain WAAS in FAA's Air Traffic Services organization, and of course the people performing the development work in Raytheon's Fullerton plant.

**The need for these skills continues.**

- **Facilitate closure of technical issues to assure LNAV/VNAV commissioning**
- **Define technical evolution of WAAS to APV and GLS capability**
- **Include tasking to**
  - *Monitor development and acceptance testing*
  - *Validate new requirements and oversee algorithm definition*
  - *Define hardware and software requirements*
  - *Allocate functional and performance requirements*
  - *Conduct trade studies vs performance, risk, cost, schedule*
  - *Develop and track sub-system interface specifications*
  - *Organize data collection activities to*
    - **analyze subsystem performance**
    - **develop empirical models**

January 18, 2001

The *new charter for the WIPP* should address two functions. The first and foremost requirement is for the system engineers to **facilitate achieving LNAV/VNAV commissioning**, then second is to oversee WAAS evolution to improved performance levels.

A number of tasks are listed. Key to LNAV/VNAV are monitoring and oversight of development efforts and acceptance testing. Also important is the management of any new or changed requirements--as problems are uncovered or as opportunities present themselves, the system engineers will need to assess technical feasibility and merit versus cost and schedule impact. Hard choices may be required--a seemingly simple change may have great potential benefit but may put the LNAV/VNAV commissioning at risk--and **without LNAV/VNAV, there is no WAAS to evolve**.

*While LNAV/VNAV is the top priority and nothing should be allowed to delay it, some of the evolutionary steps need to begin, with appropriate level of support, as soon as possible.* LNAV/VNAV will be achieved with the hardware and software and subsystem allocations already defined in the current WAAS architecture. As the system evolves to APV and GLS performance, it is likely that some reallocation of functions among components and subsystems may be necessary. The system engineers will play a key role in overseeing the tasks needed to accomplish these trades, while enforcing cost and schedule discipline.

***Early Use of WAAS***

***(Prior to Commissioning Initial LNAV/VNAV Capability)***

**January 18, 2001**

WAAS is on the air and broadcasting differential GPS corrections that routinely provide 1-2 meter accuracy. *FAA Technical Center test pilots report that WAAS vertical guidance is more stable than most ILS glide slopes.* FAA is developing LNAV/VNAV procedures for airports and runways throughout the country.

Raytheon, the WAAS developer, currently operating the pre-commissioning WAAS signal, reports that whenever the signal is taken off the air for software upgrades or other reasons, its switchboard and e-mail lights up with users seeking information on what happened and when the signals will return.

*Non-aviation uses of WAAS are proliferating*, as the WAAS signal is on the GPS L1 frequency and requires little modification to receivers to capitalize on it. Precision farming applications have sprung up throughout the WAAS service volume in North America, and U.S. and Canadian companies are selling equipment to farmers to capitalize on this free national resource. Ironically, the one "aviation related" application is crop dusting--these aircraft are not "navigating" with WAAS but are using WAAS signals to establish and maintain consistent spraying patterns and to document spray on/off locations for environmental and other records.

So it would seem natural to seek some means of *allowing WAAS operational use for its primary user community--aviation users.*

- **WAAS signals are available**
  - *Demonstrating consistent 1-2 meter (1\_) accuracy*
- **Commissioning of LNAV/VNAV now scheduled for 2002-03**
- **Non-aviation users benefiting from WAAS now**
  - *Precision farming applications*
- **Leverage user interest - e.g., FAA's CAPSTONE in Alaska**
- **Build and strengthen aviation community support**
  - *Enhance credibility of WAAS*
  - *Obtain user feedback on performance*
  - *Stimulate equipage*
- **Aviation users seek approval of some WAAS capability**
  - *General Aviation for improved access*
    - [AOPA President request to Administrator]
  - *Cargo airlines for efficient ground operations*

January 18, 2001

*Aircraft operators, especially general aviation operators, are eager to realize the benefits of WAAS. It has been widely publicized that WAAS signals are available and are providing the accuracy that WAAS was designed for. AOPA President Phil Boyer has told FAA Administrator Jane Garvey that GA users are impatient to be able to use the system.*

In addition, the Cargo Airlines Association wishes to use WAAS in connection with its evaluation of potential ADS-B applications. The additional accuracy provided by WAAS may be important in providing situational awareness on the airport surface.

FAA's own CAPSTONE program in Alaska, although not currently using WAAS, would benefit from the additional accuracy it provides. As reported to the IRB, potential expansion of CAPSTONE to Southeast Alaska and using WAAS could enable, for example, IFR LNAV airways in fjords to connect remote communities to population centers. It is envisioned that WAAS would add a margin of safety to allow air ambulances and air taxis to get through in emergency situations.

The current expectation is for formal commissioning of WAAS LNAV/VNAV capability in early 2003; *to prime the user equipment pump, some safe early capability would be beneficial.* Aircraft operators are reluctant to spend extra to purchase WAAS-capable avionics on the promise that they may be able to use WAAS capability sometime in the future. If it were possible to make at least some limited use of the WAAS prior to formal commissioning of LNAV/VNAV service, it would enhance the credibility of the WAAS schedule and motivate users to equip.

- 1. WAAS lateral navigation (LNAV)**
  - Use WAAS corrections to improve lateral accuracy
  - Provide integrity by GPS/RAIM
- 2. WAAS vertical guidance (VNAV) with automatic barometric altitude cross check - (includes option 1)**
  - Use WAAS corrections for horizontal and vertical guidance
  - Provide lateral integrity by GPS/RAIM (as in option 1)
  - Provide vertical integrity by comparing WAAS to barometric altitude via encoding altimeter interfaced to WAAS receiver
- 3. WAAS vertical guidance (VNAV) with procedural barometric altitude cross check - (includes option 1)**
  - Same as option 2 but manual comparison between WAAS and barometric altitude by pilot
- 4. Local WAAS monitor to confirm LNAV/VNAV availability**
  - External WAAS integrity check at landing site
  - Go/no-go signal transmitted to aircraft

January 18, 2001

The FAA Satellite Operations Integration Team (SOIT) identified four possible options for early use of WAAS that were both safe and had benefit to users. These were discussed first in a meeting of the Satellite Navigation Users Group (SNUG, composed of ATA, AOPA, CAA, NBAA, RAA, AHA, and DoD), then briefed to the IRB, and finally reviewed at the November 2000 SOIT meeting.

The first, *WAAS Lateral Navigation*, uses the WAAS corrections to enhance lateral position accuracy. Integrity is provided by comparing the WAAS position with the GPS/RAIM position. Use of WAAS in this mode will allow users to assess the utility of highly accurate lateral positioning in ground operations, especially in combination with ADS-B. Because integrity is guaranteed only to the basic GPS level, however, it will not allow any flight operations which require the WAAS accuracy.

The next *two options use the on-board barometric altimeter to verify the accuracy of the WAAS altitude*, i.e. to provide vertical integrity. As in the first option, lateral integrity is provided by comparison of the WAAS position with the GPS/RAIM position. The first of these barometric altimeter alternatives performs the comparison *automatically*, using the output of an encoding altimeter interfaced with the GPS receiver. The second depends on the pilot to verify *manually* the WAAS altitude with the barometric altitude. Either of these options should allow the aircraft operator to fly LNAV/VNAV approaches, gaining the safety benefit of a stabilized vertical approach.

The final option uses a *WAAS receiver at a known position on the ground* in the vicinity of an airport to verify that the WAAS corrections are valid for all GPS satellites in view. A signal is then transmitted to the aircraft indicating that WAAS may be used for guidance. Absence of the signal, or a negative (or “do not use”) signal, would indicate that WAAS should not be used.

- **Combination of options 2 and 3 provide**
  - *Both include option 1*
  - *Safety benefit of stabilized vertical approach*
  - *Capability approaching LNAV/VNAV minimums*
  - *Familiarity with WAAS accuracy*
  
- **All options require**
  - *FAA guidelines/procedures*
  - *Voluntary user equipage*
  - *Receivers that apply WAAS corrections with non-WAAS integrity*

**Alaskan Users Couldn't Wait**  
[FAA's CAPSTONE Program]

January 18, 2001

*Options 2 and 3, which both include 1, appear to have significant safety benefit, and also provide operational benefit of LNAV/VNAV approaches. Users that choose to equip will gain experience with WAAS, others will hear of this, and FAA will receive feedback on WAAS performance.*

*Guidelines must be promulgated. Also WAAS receivers must be allowed to apply WAAS corrections using either WAAS integrity if available or the external verification.*

*Use of external integrity is also a consideration discussed in Appendix J on the use of Differential Receiver Autonomous Integrity Monitoring (Differential RAIM, or DRAIM).*

*It is clear to the IRB from the Alaska CAPSTONE experience that users see a benefit in safely using these new technologies; FAA can not only gain user support for its new initiatives but also learn from these early uses of new capabilities.*



***Evolution of WAAS to Full Capability  
Actions & Payoffs***

**January 18, 2001**

WIPP presented a model for the evolution of WAAS capability from initial commissioning of LNAV/VNAV to APV to full GLS, or CAT I equivalent, performance. WIPP's model is endorsed and discussed further in the basic report's longer term recommendations.

*A key issue is that the IRB feels the major cost and effort is getting to the first commissioned use of LNAV/VNAV. Once that is done, WIPP has outlined a series of cost effective improvements in WAAS that should allow the system to evolve over time to continually improved performance levels. Attaining decision heights of less than 300 feet clearly has safety and economic benefits to large numbers of users.*

LNAV/VNAV will provide a Vertical Protection Limit (VPL) of 50 meters; the initial commissioned system will provide this more than 95% of the time over at least 50% of the conterminous US (CONUS). This capability should allow decision heights of 350 to 400 feet over most of landing locations, depending on local terrain and other factors.

*From this initial capability, WAAS will evolve.* Improvements recommended in the basic report will increase availability and increase coverage, to include the entire service volume. Over time, as both GPS and WAAS are upgraded, performance will continue to improve to allow APV landing capability and eventually GLS.

VPL essentially sets the lowest height above terrain which is acceptable on a vertically guided approach.

## Potential Evolutionary Timeline

F-2

<u>GPS &amp; WAAS Events</u>	<u>Aviation Capability</u>
2003 <ul style="list-style-type: none"><li>– First L2 GPS satellite</li><li>– One additional WAAS GEO</li></ul>	Initial LNAV/VNAV capability <ul style="list-style-type: none"><li>– 95% availability, 50% of CONUS</li></ul>
2005 <ul style="list-style-type: none"><li>– First L5 GPS satellite</li><li>– Improved and additional WRS sites</li></ul>	Full LNAV/VNAV capability <ul style="list-style-type: none"><li>– Coverage throughout CONUS &amp; Alaska</li><li>– Improve availability</li></ul>
2007 <ul style="list-style-type: none"><li>– Improved WAAS architecture</li><li>– 4 Nav package WAAS GEOs</li></ul>	Initial APV capability <ul style="list-style-type: none"><li>– Availability &amp; coverage may be limited</li></ul>
2009 <ul style="list-style-type: none"><li>– GPS L2 IOC</li><li>– GPS L5 capability grows</li></ul>	Full APV capability <ul style="list-style-type: none"><li>– Dual frequency avionics proliferate</li></ul>
2011 <ul style="list-style-type: none"><li>– GPS III begins</li></ul>	Initial GLS capability <ul style="list-style-type: none"><li>– Possible with single frequency but dual preferred</li></ul>
2013 - 2015	Full GLS capability
January 18, 2001	

When WIPP outlined its path to GLS, it identified milestones in WAAS-provided aviation capability (“payoffs”) similar to those shown in the right hand column above. The IRB felt that it would be reasonable to expect these increments in capability to arrive at approximately two-year intervals beginning with WAAS LNAV/VNAV commissioning in 2003.

The left hand column lists planned GPS and projected WAAS events (“actions”) that would occur in those same two-year increments. Projected WAAS events are based on recommendations in the basic report and elsewhere in the Appendices. For example, **the IRB has consistently recommended FAA acquire one additional WAAS GEO as soon as possible.** Appendix H discusses examples of opportunities to get this additional GEO capability expeditiously, which could produce on-orbit capability in the same timeframe as when LNAV/VNAV is initially commissioned. This new GEO would not only provide needed redundancy in the WAAS integrity/correction messaging channel, but it would also provide additional ionosphere pierce point measurements to significantly improve WAAS coverage.

Note also the timeframes during which the second civil signal (L2) and third (L5) become available. As noted in the basic report, *the IRB feels that assured GLS and APV capabilities will rely on dual frequency avionics; as discussed in Appendix I and shown above, these benefits will accrue more quickly as WAAS takes advantage of L2.*

***WAAS Synergies with Other National Systems***

**January 18, 2001**

Since the mid-90s the Department of Transportation (DOT) has been fielding civil GPS augmentations:

- the *USCG Maritime DGPS* service achieved full operational capability in 1999;
- Federal Railroad Administration (FRA) sponsored USCG expansion of this service throughout interior areas of the country for terrestrial users, and this expansion, called *Nationwide DGPS or NDGPS*, is currently well underway;
- FAA has designed and is in process of implementing *WAAS and its Local Area Augmentation System (LAAS)*;
- Maritime DGPS and NDGPS, and other US Government provided reference stations are being integrated into the National Geodetic Survey's (NGS) *Continuously Operating Reference Station (CORS) network*, which provides a post-processing database of GPS L1 and L2 observables for surveyors and other precision users.

Additionally, the *Department of Defense (DoD)* has monitored and controlled GPS via a *worldwide network of dual frequency, secure reference stations*. The National Imagery and Mapping Agency (NIMA) has also installed a worldwide network of similar reference stations, which are in process of being integrated into the GPS monitor and control network.

**The IRB has found some areas where WAAS, and also LAAS, can clearly benefit by tighter integration with these national resources.**

- **WAAS GEOs with navigation package support to LAAS**
  - *Provide additional ranging signals*
    - Mitigates shading and improves accuracy
  - *Reduce/eliminate need for pseudolites*
  
- **LAAS dual frequency reference stations support to WAAS**
  - *Provide robust network of additional reference stations*
  - *Reduce/eliminate need for additional WAAS reference stations*
  - *Allow less costly communications to multiply redundant sites*
  
- **NDGPS & CORS support to WAAS**
  - *Provide sites for additional “rim” reference station coverage*
  - *Provide data for “end around” WAAS integrity verification*
  - *Provide long term WAAS performance data for analysis*

**January 18, 2001**

*WAAS GEOs with navigation package provide ranging accuracy comparable to DoD GPS signals but from a simpler payload. The significantly improved geometry and ranging signal accuracies of a four-GEO WAAS constellation should mitigate, and quite possibly eliminate, the need for pseudolites in LAAS applications. See Appendix H for a discussion of WAAS GEOs.*

*At the moment, LAAS has committed to a single frequency certified receiver, although the other programs use dual frequency receivers. As a local area system, intended for a limited range (about 35 miles), LAAS engineers did not need to model the ionosphere--so an L1-only receiver was more economical. But for CORS purposes, for additional smoothing, and for ease of upgrade, a LAAS receiver capable of receiving all GPS signals would be better.*

*Within DOT, the USCG's Navigation Center is deploying NDGPS to meet maritime, rail, road, and other terrestrial navigation needs. These sites are integrated into the CORS network. Several of these locations are ideal to mitigate WAAS shortcomings, such as “rim” coverage in CONUS. While not certified to aviation safety requirements, NDGPS reference stations can be modified to provide additional GPS and WAAS observations to the FAA, which might be used to supplement primary WAAS observations from WRS (and LAAS reference stations).*

*In WAAS, current WAAS reference station (WRS) receivers are very expensive, but they are not certified. As WAAS improves to APVIGLS performance, certified receivers and “federated” processing at WRS locations would provide significant benefits. This is an opportunity to consolidate resources with LAAS and develop and maintain only one receiver (e.g., an upgraded LAAS receiver) to serve all civil government needs.*

- **Synchronize WAAS time to the national time standard**
  - *Install WAAS reference station (WRS) at USNO*
    - Provides WAAS direct access to USNO master clock
    - Allows USNO to closely monitor WAAS network time
  - *Install WRS at GPS Master Control Station (MCS)*
    - Provides WAAS network time to GPS ensemble clock
    - Provides WAAS access to USNO alternate master clock
- **Improve WAAS by using real time monitored data from NIMA & GPS reference stations**
  - *Provides global, secure “ionosphere-free” GPS observations*
  - *Eliminates WAAS uncertainties regarding rising GPS satellites*
  - *Expands data exchange capability between WAAS & GPS*
  - *Facilitates WAAS and GPS cooperation (eg, in GEO operations)*

January 18, 2001

The US Naval Observatory (USNO) in Washington, DC, maintains the time standard for DoD--the master clock. The GPS constellation is synchronized to universal coordinated time from USNO (UTC(USNO)); to facilitate this, the USNO alternate master clock is located at the GPS master control center in Colorado Springs, CO. Because GPS is a worldwide reference for positioning and timing information, UTC(USNO) as implemented in GPS has rapidly become a worldwide standard for time.

WAAS maintains its own master clock, synchronized to UTC(USNO) by means of measurements of the GPS satellites. This is critical so that WAAS ranging signals will be compatible with GPS ranging signals. *Far tighter synchronization of WAAS is possible by giving WAAS direct access to both the USNO master and alternate master clocks.* This could be done by siting a WRS at USNO and at the GPS reference station in Colorado Springs.

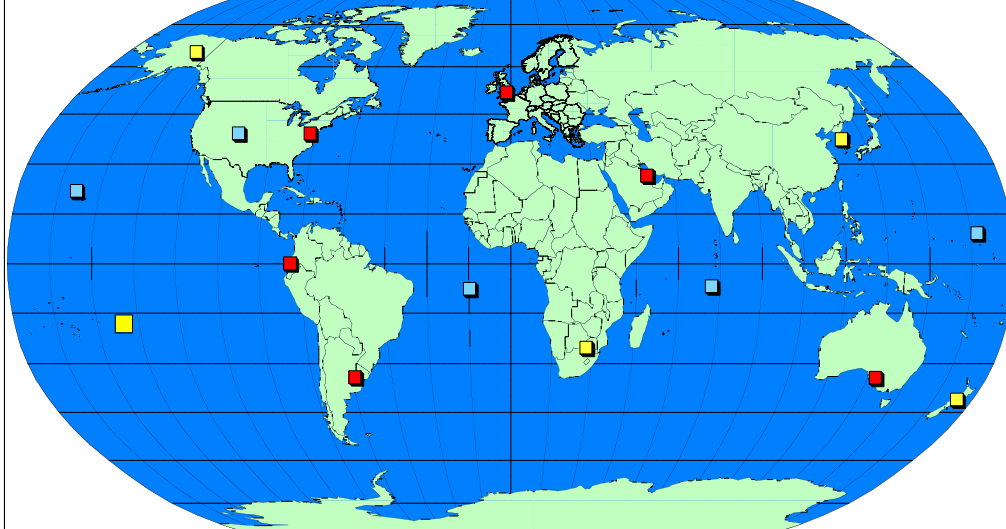
*NIMA and GPS reference stations comprise a worldwide network of dual frequency reference stations which receive the secure military signals.* The GPS reference stations are currently used in the control algorithms for GPS. The NIMA reference stations will soon be integrated with them. See chart on page G-4. *Data from these sites can be used by WAAS to eliminate uncertainty about rising satellites,* and can also be used to augment the FAA's National Satellite Test Bed (NSTB) data analyses to update models of WAAS performance parameters.

Obtaining data from this network and providing WAAS observations to the GPS master control center would be one way to start a tighter integration of GPS and WAAS. *This would be especially beneficial for all in the operation of WAAS navigation package GEOs (see Appendix H).*

## ***NIMA & GPS Reference Station Network***

**G-4**

**Monitors & Records Real Time GPS Status Worldwide (<6 second delay)**



**■ Air Force Monitor Station ■ NIMA AII Station ■ NIMA Station**

**January 18, 2001**

These are the worldwide locations of NIMA and GPS (DoD/USAF) reference stations. While they may not include aviation certified receivers, they provide a wealth of information about GPS satellite performance around the world. This information would be useful, in real time, to make rising satellites more useful to WAAS more quickly, and in a post-processing sense, to further analyze WAAS performance.

**WAAS GEO Opportunities**  
**(Satellite Acquisition and Capabilities)**

**January 18, 2001**

The current two geosynchronous satellites (GEO) in WAAS are hosted “bent pipe” payloads on INMARSAT communications satellites. COMSAT, the U.S. INMARSAT partner, provides the payloads and ground control at economical rates. FAA does not have to “fly” the GEOs; that service is provided by INMARSAT. FAA is also fortunate in that COMSAT provides the ground uplink stations (GUS) for the WAAS signal on these GEOs.

There are downsides to this, however. The downlink bandwidth of the WAAS signal is limited to approximately 2 MHz, significantly less than the 24 MHz bandwidth used in GPS L1 signals. Transmitted signal bandwidth is important, as it enables receivers to use “wide correlator” technology for significantly improved interference and noise rejection.

Another downside is that the WAAS payload is a transponder, a “bent pipe,” which simply rebroadcasts a signal received from the ground. This means that any perturbation of the uplink signal is rebroadcast on the downlink.

*DoD is evolving GPS to provide three civil frequencies; great care should be taken to phase synchronize the three carriers and their code modulations. This will allow much greater accuracy, including ionospheric calibration. With a bent pipe payload, it will be impossible for WAAS to do this with the same reliability and with the full accuracy of DoD GPS signals. Hence FAA's WAAS signals would not contribute full accuracy ranging.*

- **Approach - continued improvement in WAAS capability**
  - *Short term (24-36 months) - “buy time” for longer term solution*
  - *Longer term (36 plus months) - get best capability as available*
  
- **Short term, GEO single thread to failure - get one now**
  - *Interagency opportunities exist for 2002/03 launch, e.g.,*
    - *NASA - upgrade TDRS J, launch in 79W slot, move TDRS H*
    - *Thru DoD - partner with TELESAT Canada to upgrade ANIK F3*
  - *For WAAS signal redundancy AND improved WAAS coverage*
    - *“Bent pipe” okay - “quick & good” better than “late & perfect”*
  
- **Longer term, transition to full WAAS GEO constellation**
  - *4 GEOs, each with 3-frequency navigation package*
  - *RFI-RFP acquisition and/or partner with DoD, NASA, NOAA*

January 18, 2001

The IRB believes that to meet availability requirements in the end state of WAAS, and also in LAAS, future GEOs must be sources of accurate ranging data; This can only be done with autonomous navigation packages on the GEOs.

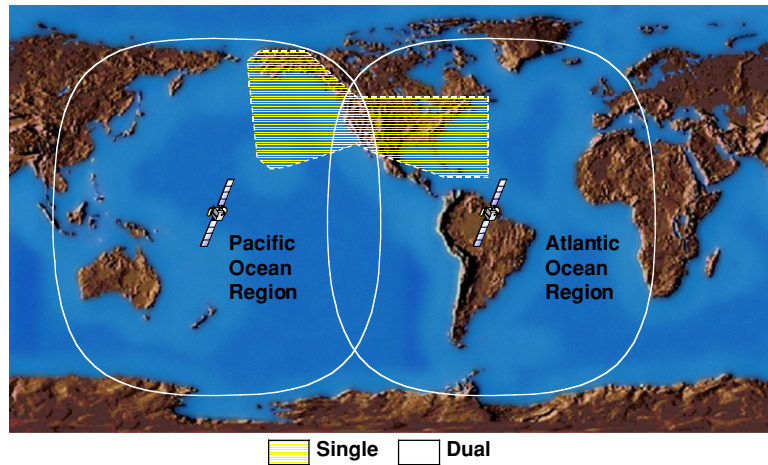
**In the near term, however, WAAS is single thread to failure**, as both INMARSAT GEOs are required to cover the WAAS service volume. See chart page G-3. At least one more GEO, located approximately midway between the INMARSATS, is needed as quickly as possible. This would serve two purposes; the primary one is redundancy over most of the WAAS service volume, the second is more ionosphere pierce points to significantly improve verification of the ionospheric correction in LNAV/VNAV capability. With attention to several technical considerations, their ranging signals would also add to WAAS availability and continuity.

*In the near term, the IRB found there are several opportunities for seeking a government partnership for a third transponder or “bent pipe” GEO within two years.*

There are many technical issues to resolve in selecting end state GEOs, and FAA is approaching this through the formal acquisition process, which requires 1-2 years to determine the best solution, then 2-4 more years until on-orbit capability. **The IRB feels the end state be four ideally placed GEOs, each with a navigation payload capable of all GPS signals on L1, L2, and L5.**



## Short term problem - limited INMARSAT Coverage



January 18, 2001

The area of dual coverage from the current INMARSAT GEOs is limited to a small portion of the service volume--just a slice of the western portions of CONUS. Should either GEO fail--either the WAAS navigation payload or the full satellite itself, the service volume would be cut nearly in half. The INMARSAT GEO covering the Atlantic Ocean Region is the the most critical for coverage in CONUS.

## Potential short term solution - additional WAAS GEO from NASA's TDRS constellation

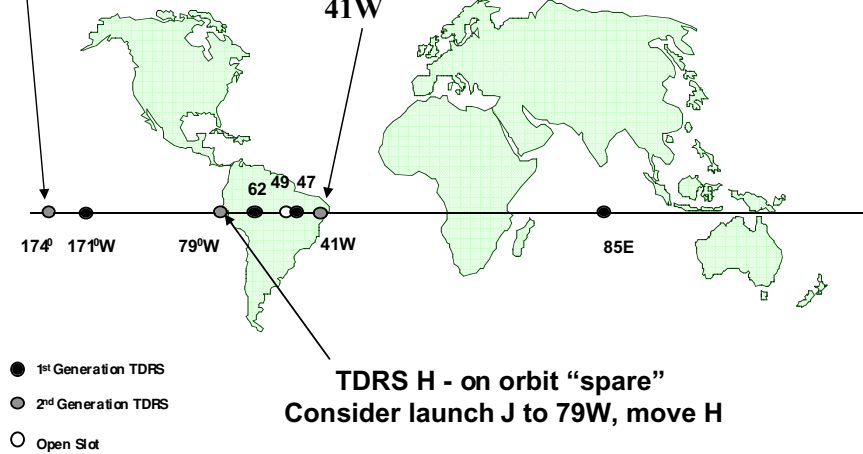
H-4

**TDRS I - planned Oct 01**

174W

**TDRS J - planned Oct 02**

41W



**TDRS H - on orbit "spare"**  
**Consider launch J to 79W, move H**

January 18, 2001

One solution briefed to the IRB by NASA would be placing a WAAS transponder on its TDRS J satellite, scheduled for launch in October 2002. This satellite is planned for 41W longitude as part of the TDRS constellation, but it could be placed in a spare slot at 79W. TDRS H is currently an on-orbit spare occupying 79W; it could be moved to 41W and operated there in lieu of J.

*Time is short to pursue this option.* TDRS I and J are built; TDRS I is essentially ready for launch and unavailable for modification. TDRS J is built and under test, but there is time to pursue a modification if action is taken quickly--by *early spring 2001*.

## Longer term need - limitations of "Bent Pipe" GEOs

- **Current WAAS GEOs use "bent pipe" payloads**
  - *Available and economical when INMARSATs obtained*
  - *FAA Accepted increased ground support required*
  - *Will support at least LNAV/VNAV performance level*
  
- **Implications**
  - *No WAAS availability improvement from GEO ranging signal*
    - **Precise code/carrier coherence cannot be maintained**
    - **Phase noise excessive due two ionosphere passes and two high frequency synthesizers**
    - **Narrow signal bandwidth severely limits receiver processing**
  - *Relatively easily jammed or spoofed*
    - **Safety maintained by shutting down transponder**
    - **At cost of WAAS availability**

January 18, 2001

Carrier smoothing of code phase measurements has been key to the dramatic improvements in accuracy in GPS ranging measurements. This is possible with DoD's GPS signals because both code and carrier are derived from the same clock on board the . With WAAS bent pipe GEO's this coherence is much more difficult if not impossible to obtain. Additionally, the key to using multiple frequency measurements and code/carrier smoothing techniques for improved ranging accuracy is the coherence of these signals at the source--aboard the satellite.

In a bent pipe WAAS payload, the code and carrier control loop must be closed around a lengthy path delay, which includes synthesizers, C band to L band downconverter, and two trips through the ionosphere--uplink and downlink. Some error sources must be modeled, and the narrow bandwidth downlink and limited measurements available within the control loop are insufficient to characterize all errors. The problem expands exponentially if WAAS transmits more than one frequency (e.g., L1, L5, and possibly L2).

As the WAAS GEOs are visible from a very large portion of the world it is possible to jam or spoof them from a wide region including several terrorist states. This jamming/spoofing can be easily detected on both the C band and L1 downlinks, but it cannot be prevented. Safety is maintained by using other control uplinks to the GEO to quickly shut down the L1 downlink; the cost is loss of WAAS availability.

## **Longer term solution - constellation of “Navigation Package” GEOs**

H-6

- **Navigation package autonomously generates signal on board GEO**
  - *WAAS ranging signals comparable to GPS in quality*
    - **But control and on-board equipment simpler than GPS**
  - *Significantly improves WAAS availability and continuity*
    - **Important for APV and especially GLS**
  - *WAAS ranging signals mitigate/eliminate need for LAAS pseudolites*
  
- **Implications**
  - *Tight code/carrier coherence maintained at signal source on GEO*
    - **Includes multiple frequencies (full GPS signal set-L1, L2, L5)**
  - *Encrypted data message uplink precludes jamming/spoofing*

January 18, 2001

*A WAAS GEO navigation package can be much simpler and cheaper than a complete DoD GPS navigation package. WAAS GEOs are continuously monitored, and their orbital positions are essentially constant as seen from the ground.*

*The WAAS data message is generated on the ground and uplinked to the GEO, but once on board, the WAAS L1 downlink signal is generated directly from the GEO's local oscillator, and the data message is applied. Code/carrier coherence on L1, and optionally L2 and L5, signals is maintained by local control loops on board, exactly as in DoD GPS satellites, so stability is comparable.*

*The additional 30 dB of jamming immunity with an encrypted data uplink means a significantly larger and more expensive jammer is required to take over the signal. Such a jamming or spoofing source would be much easier to detect, localize, and therefore eliminate.*

*Several benefits of navigation package quality signals include greater availability and continuity in WAAS at APV/GLS performance capability. Significantly, the improved geometry and ranging signal accuracies of a four-GEO constellation should mitigate, and quite possibly eliminate, the need for pseudolites in LAAS applications.*

***Dual Frequency Avionics***

**January 18, 2001**

Dual frequency GPSWAAS avionics allow *direct measurement of the ionosphere* in the aircraft. Modeling the ionosphere and detecting ionospheric storm conditions at all points in the WAAS service volume are the major sources of uncertainty in WAAS integrity calculations. This uncertainty requires conservatism, which leads to a WAAS which routinely provides 1-2 meter level accuracy but can only prove  $10^{-7}$  integrity at the 50 meter vertical protection limit (VPL). *With dual frequency avionics, much of the conservatism can be removed from the integrity calculations, and dual frequency users should enjoy a significantly smaller VPL.*

**With S/A off, ionosphere is largest error in GPS for civil users**

- **GPS has 2 frequencies - L1 (1575 MHz) & L2 (1227 MHz)**
  - *Primarily to eliminate ionospheric error and increase robustness in military receivers*
    - Receivers measure ionosphere delay on each signal directly
    - Alternative is to ignore error or model ionosphere
- **WAAS models ionosphere for single frequency avionics**
  - *Most stressing requirement in proving WAAS integrity*
  - *Limited ionosphere measurements and model convert WAAS from a 2 meter (1s) vertical accuracy into 50 meter VPL system*
- **FAA plans eventual dual frequency use**
  - *“Third” civil signal is L5 (1176 MHz) approved and planned*
  - *In protected aeronautical frequency (ARNS) band*
  - *Using L1 and L5 also corrects for ionospheric error in receiver*

January 18, 2001

GPS was originally designed with two frequencies to primarily eliminate the effect of the ionosphere. The L1 signal has two components, a C/A code and a P(Y) code, the L2 signal currently carries only the P(Y) code. The P(Y) code is encrypted for military users, and most civilian use is restricted to the L1 C/A code signal.

WAAS models the ionosphere based on measurements from each satellite in view at each WRS and provides ionosphere grid point corrections throughout the service volume. *This is the most stressing requirement in WAAS.* It could be significantly eased if avionics could measure the ionospheric delay to each satellite directly.

FAA recognized the advantages of dual-frequency avionics and worked through the Interagency GPS Executive Board (IGEB) to establish a second civil signal. Preliminary work indicated that a C/A code on L2 would provide this capability, but L2 is not in a protected aviation frequency (ARNS band) as required by FAA and ICAO regulations for “safety of life” navigation.

A third civil signal called L5 was identified and approved; L5 is in the ARNS band, and it is specifically designed to be a robust aviation signal. *Used in together with L1, when L5 becomes available on most DoD GPS satellites (and WAAS GEOs), dual frequency avionics will be capable of measuring ionospheric delays.*

- **“Second” civil signal will be L2**
  - *Unencrypted GPS L2 signal begins in 2003*
  - *Worldwide availability by 2008-10*
- **L2 is not in aeronautical (ARNS) band**
  - *FAA & ICAO require ARNS for primary “safety of life” navigation*
  - *But a signal for measuring ionospheric delay need not be ARNS*
- **GPS L5 begins 2005, with worldwide availability 2013-15**
- **Precision civil users correct for ionospheric errors and gain accuracy from L2 today**
  - *Semi-codeless tracking techniques*
  - *Survey, machine control, and aerial photogrammetry applications*
  - *Required and used in WAAS and NDGPS reference stations*

January 18, 2001

L2 and L5 will be added to the GPS constellation as current GPS satellites end their life and new ones are launched. The first L2 capable GPS launch is scheduled for 2003, with worldwide availability as shown. The first L5 capable GPS launch is scheduled for 2005, with significantly later worldwide availability. Block IIR (current replenishment GPS series) are being modified to provide L2; Block IIF (next GPS series) are being procured to include L5 as well as L2.

Several GPS receiver manufacturers have developed dual frequency civil GPS receivers which receive and track the L2 signal today using “semi codeless” technology. These have been used primarily for survey applications, but they are increasingly being used for control of mining, construction, and agricultural equipment. Also note that the WAAS and NDGPS reference stations are equipped with (and need) dual-frequency receivers which use these semi-codeless techniques, and NDGPS L1 and L2 data are used in the NOAA National Geodetic Survey’s continuously operating reference station (CORS) network.

**L5 is the second “safety of life” signal, but L2 will be available for ionospheric calibration sooner**

- **Advantage of using L1 and L5**
  - *Ionospheric correction when both are available*
  - *Navigation redundancy when one is not available*
- **Advantage of using L2**
  - *Obtain ionospheric correction sooner - L1 and L2*
  - *Ionospheric correction redundancy when L5 available*
    - L1 and L5, or L1 and L2
    - L2 and L5 may also provide ionospheric correction
      - *May require limited modeling capability in receiver*
      - *Requires further study*
- **Semi-codeless L2 use**
  - *Would provide ionospheric correction now*

January 18, 2001

When L5 is available, aviation users will have both a redundant signal for navigation and the ability to measure the ionosphere. But they will have *access to the fully functional civil L2 signal sooner*. Since L2 is not in the ARNS band, this will only yield ionosphere calibration measurements.

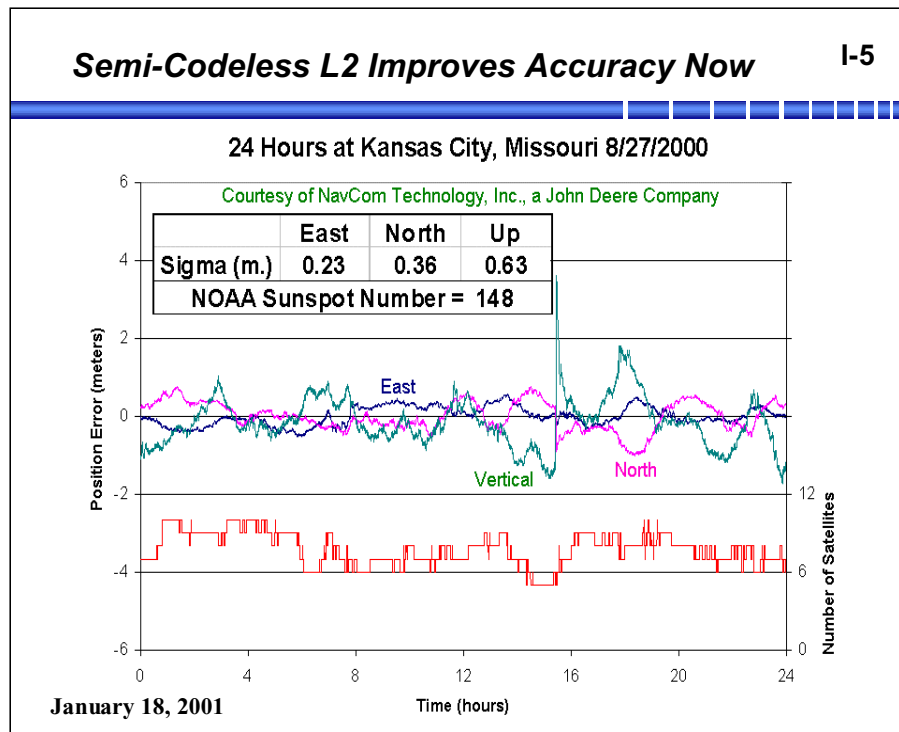
If L2 is kept in the avionics when L5 is available, these users will have redundancy on both the ionosphere and in navigation. The use of L2 and L5 together to measure the ionosphere needs more study.

Aviation users, like many surveyors and other terrestrial users, could consider semi-codeless L2 use now. Some aviation applications, such as aerial photogrammetry, have successfully done so in their “truth” system data. See data on charts I-5 and I-6.



## Semi-Codeless L2 Improves Accuracy Now

I-5



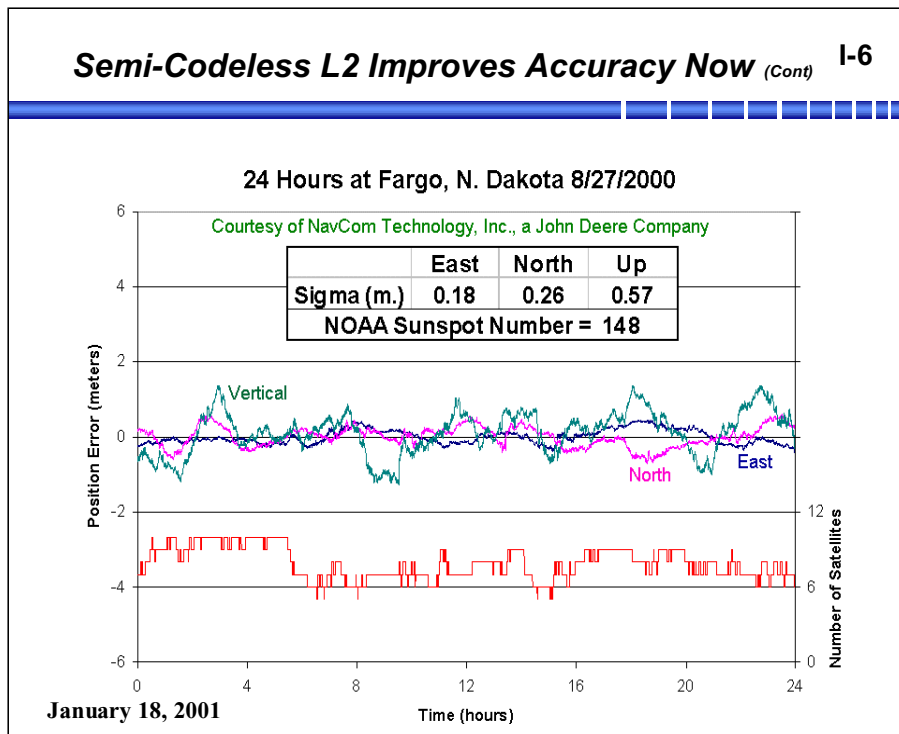
The purpose of this and the following plot is to show that *use of L2 today* is practical and leads to quite good vertical and horizontal accuracy over North America, with a reference station network much smaller than that of WAAS.

These two charts show 24 hour plots of north, east, and vertical error for the StarFire system. StarFire was developed and is operated by NavCom Technology, Inc., a John Deere Company. Although the main purpose of StarFire is horizontal positioning for agricultural applications, the vertical accuracy performance is superb, primarily because it employs dual-frequency (L1/L2) user equipment to eliminate ionospheric error. The DGPS data from the ground support network corrects only for GPS clock and orbit errors.

StarFire is a DGPS service provided throughout North America via a centrally-located GEO. (The GEO does not provide ranging signals.) There are only about seven ground reference stations in the StarFire network.

Paul Galyean of NavCom Technology, a member of the WIPP, provided these data and authorized inclusion in this report. He included the following comment about the plot above: "Aside from the general accuracy, you will notice one spike in altitude up to 3.6m. That is at a point where PDOP got quite large as the number of usable GPS satellites dropped to five." This supports the IRB recommendation for robust ranging signals from 4 WAAS GEOs, which in addition to other advantages would eliminate or significantly mitigate "PDOP spikes."

## Semi-Codeless L2 Improves Accuracy Now (Cont) I-6



These StarFire data did not have a PDOP problem, as in the previous plot. As a result, the vertical error never exceeded two meters and seldom exceeded one meter.

WAAS can achieve this level of accuracy or better, as well as improved availability, for users with properly designed dual frequency receivers. One requirement is that UERE values be reduced substantially. (There is full agreement this can be achieved.)

We recommend that the WAAS program evaluate L2 use, and if it proves to be as effective and robust as these data indicate, it should not only be allowed but also encouraged by publishing approaches with lower minimums for properly equipped aircraft.

***Differential RAIM (DRAIM)***

**January 18, 2001**

RAIM and DRAIM are techniques for determining GPS integrity autonomously.

## **RAIM - Receiver Autonomous Integrity Monitoring**

- **Technique to Flag and Isolate unusual GPS ranging errors - based on residual ranges**
  - **Requires over 4 satellites** *[typically 6 to 11 in view]*
  - **Basis for “self” integrity checking**
  - **Isolation dependent on geometry** *[more satellites help]*
  - **Requires estimate of “usual” error statistics**
- **DRAIM - RAIM applied to differentially corrected ranging**
  - **Concept like RAIM but errors partially correlated**
  - **Not yet extensively studied**
  - **WAAS application** *[with precision GEOs, 9 to 15 satellites in view]*
  - **Manufacturers developing receivers with 14 and 15 GPS/WAAS signal channels**

January 18, 2001

The concept of RAIM, or Receiver Autonomous Integrity Monitoring, has been studied for many years. Briefly it is a technique that uses an excess of measurements to check whether one or more are anomalous, and discard the anomalous ones from the solution. *Since GPS requires four satellites to navigate, all ranging measurements over four (the “excess”) allow some RAIM determination to be made.*

The strength of the RAIM solution depends on both the geometry of the ranging sources and the number of excess satellites. As might be expected, the isolation capability becomes very strong when the excess is four or more. The basis for the estimate includes an understanding of the size of the normal ranging errors.

*The idea of DRAIM (Differential RAIM) is to use the same concept, but apply it to differentially corrected ranges.* Because the WAAS correction process can introduce correlations between the satellites, the usual technique must be modified. Some studies have been performed for LAAS, but the IRB knows of no definitive study for WAAS.

Note that the advent of precision ranging GEOs (advocated by the WIPP and the IRB) will significantly strengthen the capability, with up to 3 additional ranging sources. The “excess” will range from five to eleven. (See Appendix H.)

Note also, that avionics manufacturers are prototyping 14 and 15 channel receivers, which will allow the user to take advantage of this cross check at negligible incremental cost. (See Appendix K.)

- **Appealing alternative check on integrity**
- **With 5 to 11 “extra” measurements, WAAS has powerful statistical leverage**
- **Must avoid current conservatism in WAAS ranging error statistics**
- **Particularly appealing with use of 2<sup>nd</sup> Freq.**  
[eliminating correlations of the ionospheric errors]
- **Requires modifications to MOPS, etc.**

**Bottom Line - Needs Further Study**

***Potentially leads to earlier availability  
-may provide simpler system architecture***

**January 18, 2001**

WAAS is a particularly appealing target for the RAIM (and DRAIM) techniques. *The extra ranging signals from WAAS GEOs will make it a more robust solution.* With the advent of the second frequency in a few years, the concept will be further simplified. This is because the correlations of ionospheric errors will virtually disappear.

To be useful in a certified receiver, the MOPS and other FAA documentation will have to be modified to allow use of WAAS corrections with integrity provided by WAAS or by RAIM/DRAIM. Because this has a long lead time, it is important that the concept be studied and validated as early as possible. Note that these changes are also required for some early uses of WAAS, as outlined in Appendix E.

The bottom line is that *DRAIM definitely warrants further study*, since it potentially could lead to earlier availability and a simpler system concept.

**WAAS Avionics Developments**

**January 18, 2001**

A limited IRB review indicated that general aviation users will equip with WAAS avionics if they see a *safety* need, if they gain improved runway access, or if the system provides useful additional features; but cost will be a significant factor. Similarly, for commercial users, equipage is strongly driven by the *business case*, as well as by *safety* requirements. The requirement for *Enhanced Ground Proximity Warning System (EGPWS)* in new commercial aircraft by 2003, and fleet wide by 2005, provides an opportunity to equip with GPS. *Runway incursion prevention* also provides incentive for these users to equip.

The IRB was briefed on the FAA's CAPSTONE program in Alaska, which integrates GPS, ADS-B, and other new capabilities in avionics to provide the equivalent of radar-controlled flight without air traffic control radars. Initial positive user feedback and FAA consideration of expanding the program to include use of WAAS are evidence that users will equip if they see a benefit.

To that end, the IRB reviewed avionics manufacturers' plans to incorporate WAAS. These are summarized on the next two charts.

## Key WAAS Receiver Developments

- **UPS Aviation Technologies – GPS/WAAS engine**
  - 15 channels - GPS all-in-view plus WAAS ranging signals
  - RAIM integrity monitoring
  - Will become heart of their ADS-B system
- **NavCom Technologies – NCT-2000D GPS engine**
  - Dual Frequency L1/L2
  - 2 additional WAAS channels
- **NovAtel – Millennium WAAS Receiver**
  - Dual frequency (L1/L2) to correct for ionosphere delays
  - 12 L1 C/A GPS Code tracking, 4 L1 C/A WAAS code tracking
  - Other L1/L2 combinations
- **Thales (formerly Thompson) – L1/L2 GPS/GNSS engine**
  - 16 Channel L1 receiver, 12 Channel L2 receiver
  - Correction protocols for WAAS/EGNOS/MSAS

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At least *ten different WAAS avionics developments* are currently underway; some of the more significant are shown here. They include new OEM GPS/WAAS engines, new receiver developments, and some also have capability to receive and process other signals (e.g., GLONASS, EGNOS, MSAS). Most early developments target high end capabilities and users, and include multi-mode receivers (GPS, WAAS, LAAS, ILS). There undoubtedly other developments underway but as yet unannounced, and as WAAS capability and operational utility are demonstrated, it is likely that new competitors will enter the market in significant numbers.

IRB research also found some level of WAAS receiver development activity or interest in the following companies:

- Sokkia
- Axiom Navigation
- RoyalTek
- CSI Wireless
- MAN Technologies
- Satloc
- Canadian Marconi
- Septentrio

Significantly, a number of the new receivers include extra channels for WAAS signals; this allows them to continue to track all GPS satellites in view, while adding the ability to track several additional signals from WAAS GEOs. Not only will these new receivers have redundant WAAS integrity signals (when additional GEOs are provided) but also more robust position solutions using the additional WAAS ranging signals. (See Appendix H for discussion of GEO ranging signal capabilities.)

- **Many very capable WAAS receivers will be available this year plus other “WAAS enabled” receivers**
- **The user equipment market will most likely grow from high-end users to lower end users**
  - *Economies of scale of producing original products*
  - *Market growth fueling additional development of lower end products*
- **The range of products will support the expected evolution of WAAS from LNAV/VNAV to APV to GLS**

**WAAS avionics will be available to support equipage**

**January 18, 2001**

Avionics manufacturers are interested and developing products which will take advantage of GPS, WAAS, and LAAS. It is clear that these receivers will be available within the next year.