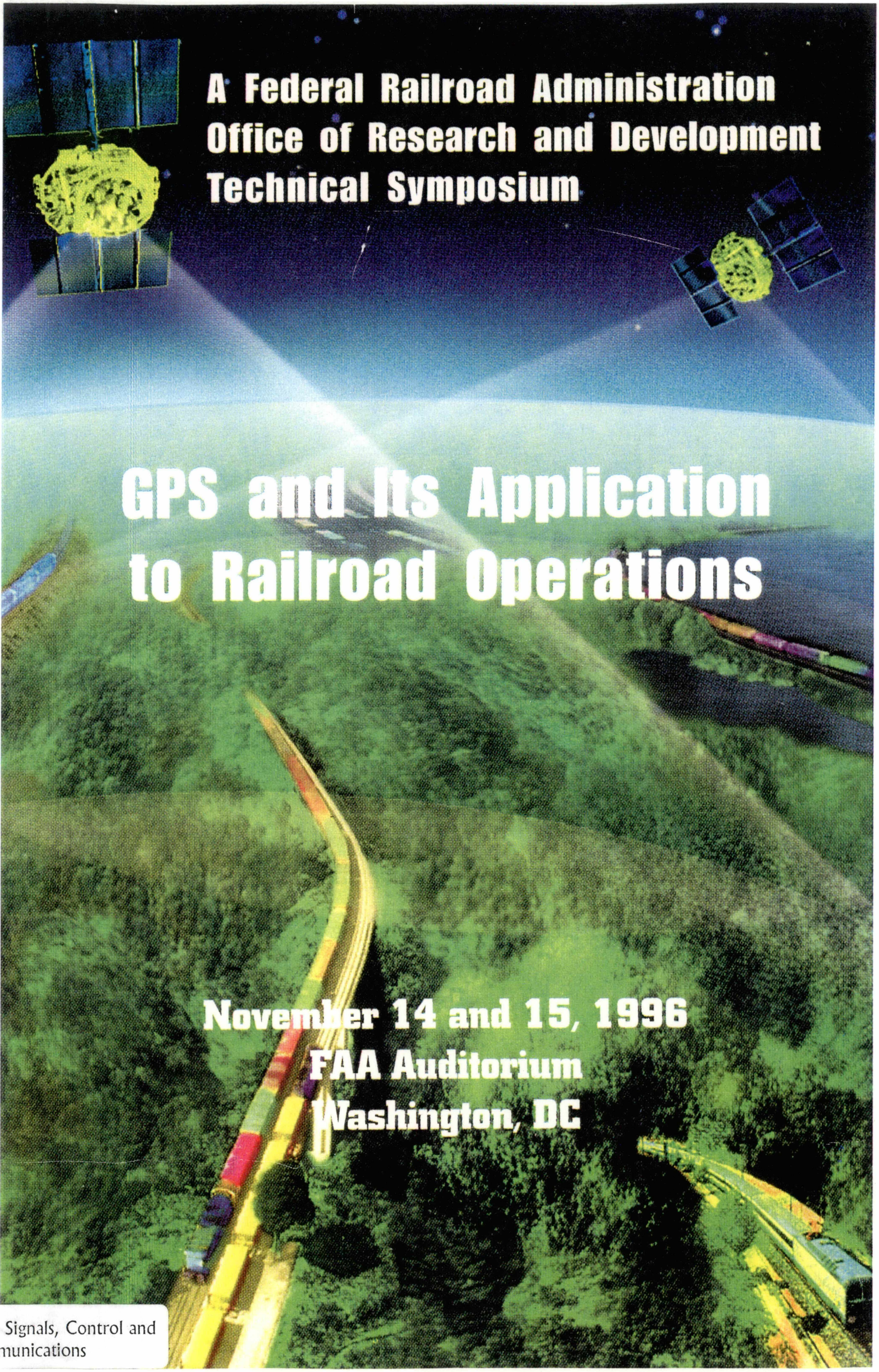


A Federal Railroad Administration
Office of Research and Development
Technical Symposium

GPS and Its Application to Railroad Operations

November 14 and 15, 1996
FAA Auditorium
Washington, DC

The **Global Positioning System** (GPS) and Its Applications to **Railroad Operations**

A Federal Railroad Administration Technical Symposium

November 14 & 15, 1996
FAA Auditorium - 800 Independence Ave., S.W.
Washington, DC

Thursday, November 14

7:30 - 8:00 am	Registration / Coffee & Light Refreshments
8:00 - 8:10 am	Introductions / Symposium Charge Steven R. Ditmeyer, Director, Office of Research &Development Federal Railroad Administration (FRA)
8:10 - 8:30 am	The FRA Perspective The Honorable Jolene M. Molitoris, Administrator, FRA
8:30 - 8:50 am	GPS: Federal Policy and Commitments The Honorable Frank Kruesi Assistant Secretary for Policy United States Department of Transportation (U.S. DOT)
	GPS BASICS
8:50 - 9:10 am	GPS - A Historical Perspective Donald Henderson, former head GPS Joint Project Office former Vice President of Operations - Burlington Northern Railroad
9:10 - 9:30 am	GPS - Future Plans Captain Mark Mayne, United States Coast Guard (USCG) U.S. DOT Representative, GPS Joint Project Office
	GPS APPLICATIONS IN OTHER MODES
9:30 - 9:50 am	U. S. Coast Guard Differential GPS - USCG Navigation Center Commander Doug Taggart, Chief, Systems Management Division
9:50 - 10:10 am	GPS Traffic Control on the Saint Lawrence Seaway Kam Chin, Manager, Center for Navigation Evaluation Laboratory U.S. DOT - Volpe National Transportation Systems Center
10:10 - 10:30 am	Break

10:30 - 10:50 am GPS Applications for Commercial Vehicle and Transit Operations
William Jones, Technical Director
Intelligent Transportation Systems Joint Project Office

10:50 - 11:10 am Kinematic GPS - Real Time Precise Docking System for Ships
Wang Tang, ARINC

11:10 - 11:30 am GPS and Aviation - Assuring Data Integrity
Richard Arnold, Chief, Navigation and Landing Division, FAA

11:30 - 12:30 pm Lunch - FAA Building Cafeteria

Technology Issues

12:30 - 12:50 pm Fault Tolerant Train Tracking / Hybrid Systems
Milton Adams, Charles Stark Draper Laboratory

12:50 - 1:10 pm GPS Receiver Performance - Reliability
George Ott, ASHTECH, Inc.

GPS AND RAILROADS

1:10 - 1:30 pm Current Requirements for Railroad GPS Use
Howard Moody, Association of American Railroads

1:30 - 1:50 pm Previous Railroad Applications and Operational Requirements
Ed Butt, Lockheed Martin

1:50 - 2:10 pm Incremental Train Control System - Amtrak Michigan Corridor
Bob Heggestad, Harmon Electronics

2:10 - 2:30 pm Pacific Northwest Positive Train Separation System
Bill Matheson, GE Harris Railway Electronics

2:30 - 2:50 pm Break

2:50 - 3:10 pm Railroad and Other Transportation Applications
Stephen Graham, Rockwell Transportation Electronics

3:10 - 3:30 pm Transferring GPS Technology from Transit to Railroads
Howard Shore - Orbital Sciences Corporation

GPS RR Symposium - Thursday, November 14th - Continued

3:30 - 3:50 pm	The Expanded Role of GPS in Commuter Rail Systems Douglas Toth, Ph.D. - GeoFocus, Inc.
3:50 - 4:10 pm	GPS / Geographic Information Systems (GIS) Condition Monitoring and Maintenance Planning J. Kevin Kesler, ENSCO, Inc.
4:10 - 4:30 pm	Summary Review - Questions
4:30 pm	Adjourn for the day

Friday, November 15

8:00 - 8:30 am	Coffee & Light Refreshments
8:30 - 9:10 am	GPS Land Applications Captain Lewis A. Lapine, Director, National Geodetic Survey National Oceanic and Atmospheric Administration
9:10 - 9:40 am	GPS R&D on East Japan Railways (JR East) , JR Freight and the Railroad Technical Research Institute (RTRI) Yutaka Hasegawa, General Manager Technical Support Division, RTRI
9:40 - 10:10 am	Dual Use Technology Success Mike Swiek, Executive Director GPS Industry Council
10:10 - 10:30 am	Break
10:30 - 11:30 am	Future Roles for GPS in the Railroad Industry - Panel Discussion Ronald Lindsey - CSX Transportation - panel moderator
11:30 - noon	Comments / Presentations from the Floor
noon	Conclusion / Adjourn

Ashtech

GG24

GPS+GLONASS Receiver

The addition of 24 GLONASS satellites to the 24 satellites of GPS has given us a system that is more reliable and more accurate than either system by itself.

By: Dr. Frank van Diggelen

Contents

GPS

When the Global Positioning System (GPS) became operational in 1993 it promised to provide a new utility, as pervasive and as useful as the telephone. For many users this potential has already become a reality. Pilots can now use GPS to find airports, mariners can find harbors, hikers can find their way, and surveyors can measure positions to centimeter accuracy. New applications have farmers, miners and construction workers guiding their machines using GPS. However, just as the telephone system had limitations that are removed with the augmentation of the system with cell-phones, the GPS system has certain limitations that become apparent in certain applications. These limitations are dramatically reduced by the augmentation of the GPS system with GLONASS satellites.

The US Department of Transportation has determined that, while GPS is usually accurate enough for navigation of airplanes, there are not enough satellites to provide the availability requirement of 99.999 percent suggested for a system used as the primary means of navigation. So, for the moment, airlines still use more expensive, less accurate, but more reliable means of navigation, with GPS is a back-up.

For marine safety, accuracy of 10m or better is often required. Navigation aids, such as buoys, are usually positioned to 10m accuracy. A GPS receiver alone cannot give this accuracy because of deliberate degradation of the signal available to civilians. A complex system of differential reference stations has been set up in many countries, allowing mariners to receive corrections for the errors added to GPS. Unfortunately the radios needed to receive these corrections often cost more than the GPS receiver itself. The White House has promised to review the policy of Selective Availability (the deliberate degradation of GPS) yearly, *starting in the year 2000.* Until then, users of GPS have a choice of less accuracy, or less of a bank-balance – if they are lucky; in parts of the world, where no differential reference stations are available, most users are stuck with accuracies of 100 meters.

Hikers may spend all day climbing a mountain, say Colorado's Pikes Peak; 14,110ft. On reaching the top their GPS receiver tells them they are only at 13,800ft. Ten minutes later the same receiver may say they are at 14,400ft. This is a result of Selective Availability, which not only produces errors, but constantly changes them. Not very reassuring for hikers hoping to use GPS in areas where an extra few hundred feet may mean the difference of being on the cliff or over the edge. Similarly, unaided GPS is not accurate enough for in-harbor navigation or for finding on which side of a highway a vehicle is traveling.

Surveyors, Miners, Farmers and others have generally solved the accuracy problem by installing their own differential reference stations. They can and do achieve position accuracies of centimeters. However, even here the constantly changing errors from Selective Availability make an impact: the radio corrections have to arrive rapidly and constantly. A few seconds of lost radio reception results in rapidly growing errors, even though the GPS receiver may be tracking several satellites.

Finally there is the problem of satellite visibility.
A GPS receiver needs to see at least four satellites to calculate latitude, longitude and altitude. For real-time centimeter accuracy five or more satellites are needed. This is easy in a perfect environment, with 24 GPS satellites orbiting the earth there are usually seven satellites visible 10° or more above the horizon. But if there is a mountain or other obstruction nearby, the number of useful satellites may fall to 4, 3 or fewer.

Summary:

- For many users GPS is a utility like a telephone, but the system has limitations.
- More satellites are needed to provide integrity for aircraft navigation.
- GPS accuracy is degraded by the policy of Selective Availability.
- More visible satellites need to be available in areas where part of the sky is blocked.
- These limitations are dramatically reduced with the augmentation of GPS by GLONASS.

GPS + GLONASS

Ask yourself this question: *"What if we could add another 24 satellites to the GPS system, but this time without any deliberate degradation of accuracy, would this remove the limitations on the system"*
The answer is: *yes!*
All the limitations discussed above would be dramatically reduced simply by convincing the US taxpayers to fork out an extra several billion dollars for another 24 satellites, and simultaneously convincing the US military that this time they should make satellites that don't degrade or encrypt the signals.

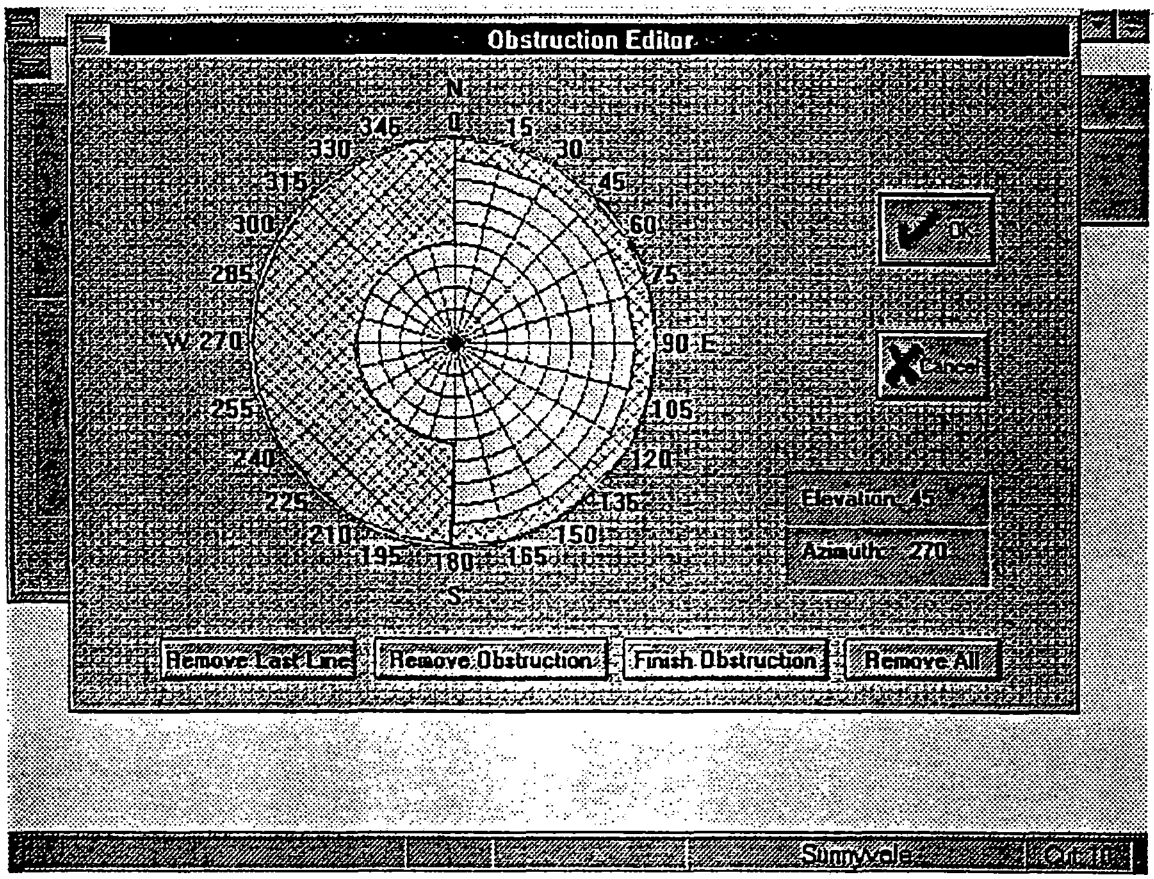
Now ask yourself another question: *"When might we expect such a system to be in place and ready to use?"*
The answer is: *yesterday!*
Believe it or not, the extra satellites needed to expand GPS to a true utility are already in orbit and operational, and they didn't cost the US Taxpayer 1 cent.
In January 1996 the Russians completed their full constellation of 24 operating satellites in the GLObal NAvigation Satellite System (GLONASS), a system almost exactly the same as GPS. GLONASS does have two significant differences from GPS however: no deliberate degradation of accuracy and no encryption of the most accurate signals.
The addition of GLONASS to GPS provides three things:
Availability, Integrity & Accuracy.

Summary:

- The extra satellites needed to remove the GPS limitations are already operational
- The addition of GLONASS to GPS gives availability, integrity & accuracy.

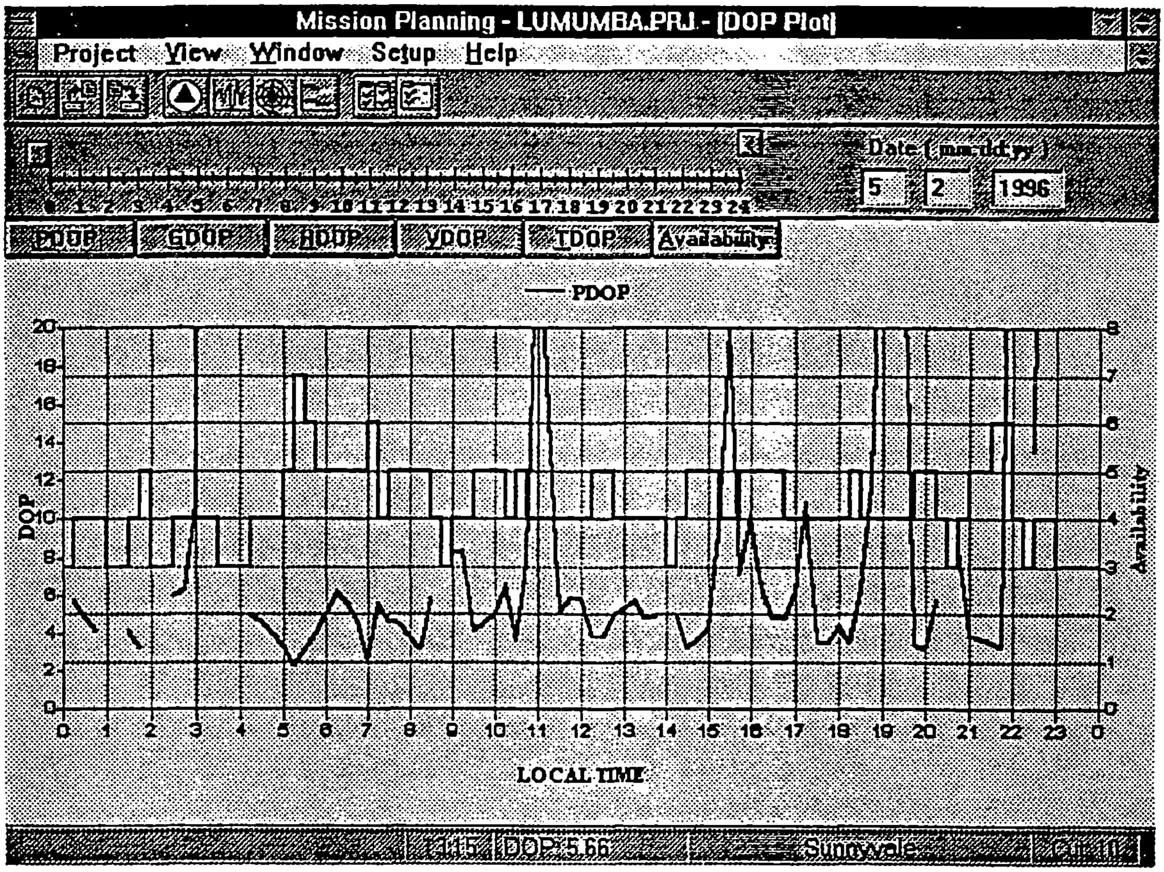
Availability

We use tools called Mission Planners to analyze how many satellites will be visible from any given location, with any known obstructions blocking part of the sky. The visibility changes depending on the latitude (more satellites are overhead nearer the equator, more are close to the horizon nearer the poles). For the purposes of this paper we chose an arbitrary point at 37° North, 122° West (this is Sunnyvale, California, where Ashtech GPS+GLONASS receivers are built and tested). We constructed an obstruction 45° above the horizon, covering the whole western sky, as well as a 10° obstruction for the eastern sky, this is shown in the figure below. Examples of this kind of obstruction are: urban canyons, especially when the user is close to a tall building; open pit mines; mountainous terrain.



Next we show the satellite availability for only the 24 GPS satellites:

Figure 1 Satellite Availability with GPS-only, and 45 degree obstruction



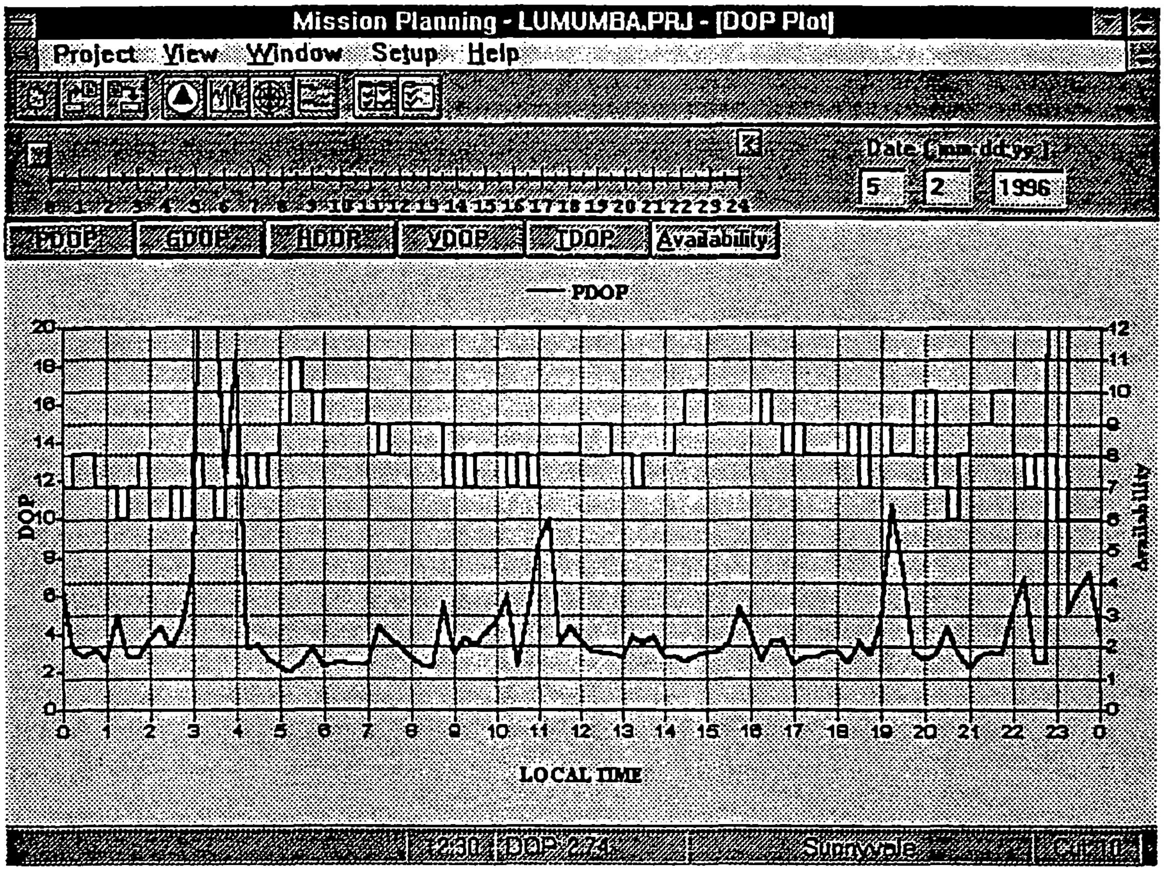
The straight lines and right-side axis show the number of satellites visible at each time through 24 hours. The broken line and left-side axis shows a value called PDOP. PDOP is a statistical measure of the accuracy of the computed 3 dimensional position and is influenced by how the satellites are spread around the sky. If PDOP doubles, then the expected position errors also double. When fewer than 4 satellites are visible then latitude, longitude and altitude cannot be calculated. When fewer than 5 satellites are available, then centimeter accuracy is not possible.

Summary: Satellite Visibility with GPS-only and 45° Obstruction

Criterion	Availability
5 or more satellites visible, real-time centimeter-decimeter accuracy[1]	33%
4 or more satellites visible, 3D position possible	86%

[1] To achieve real-time centimeter accuracy, a process known as carrier-phase ambiguity resolution is necessary, this requires 5 or more GPS satellites. If 5 or more satellites are available, and PDOP is large, then carrier-phase ambiguity resolution is still possible, but the expected accuracy will be worse.

Figure 2 Satellite Availability with GPS+GLONASS, and 45 degree obstruction



When GPS and GLONASS are used together, the receiver uses one extra satellite in the solution to account for the different reference times used by the two systems. When fewer than 5 satellites are visible then position and altitude cannot be calculated. When fewer than 6 satellites are available, then real-time centimeter accuracy is not possible.

Summary: Satellite Visibility with GPS+GLONASS and 45° Obstruction

Criterion	Availability
6 or more satellites visible, real-time centimeter-decimeter accuracy[2]	100%
5 or more satellites visible, 3D position possible	100%

These tests with a 45° obstruction were repeated at different sites, down to the equator and up to the pole. The results were very similar between 0° and 60° latitude (within 10% of the above results for GPS-only, within 5% of the above results for GPS+GLONASS).

[2] To achieve real-time centimeter accuracy, a process known as carrier-phase ambiguity resolution is necessary, this requires 6 or more GPS+GLONASS satellites. If 6 or more satellites are available, and PDOP is large, then carrier-phase ambiguity resolution is still possible, but the expected accuracy will be worse.

North of the polar circle the GPS+GLONASS results were similar, but the GPS-only results deteriorated dramatically to less than 50% availability of 4 or more satellites.

The results for the southern hemisphere are symmetrical to the northern hemisphere.

Another consequence of satellite availability is that when centimeter accuracy is possible, then the time required to achieve centimeter accuracy decreases as the number of satellites increases. The improvement of GPS+GLONASS over GPS-only is:

Receiver	Time from satellite lock, till centimeter accuracy
GPS L1	30-40 minutes
GG24 GPS+GLONASS L1	5-15 minutes

Summary:

- Availability of GPS satellites is severely restricted by large obstructions that block part of the sky, for example: buildings.
- When large obstructions block part of the sky, the availability of real-time high-precision (centimeter and decimeter) is more than doubled by the addition of GLONASS to GPS.
- The time taken to achieve 1cm accuracy is reduced by 3 to 6 times by having GPS+GLONASS.

Integrity

In a recently published study by the DOT's Volpe National Transportation System Center[3] the following findings were made:

"Unaugmented GPS has an availability of approximately 60 percent for nonprecision approach [NPA], resulting in outages that last up to 295 min at a specific location."
"The availability of GPS to perform fault detection and exclusion [FDE] during nonprecision approach is less than 50 percent over the CONUS [Conterminous United States]."
"For oceanic, en route, and terminal navigation ...outages can last more than 0.5h during oceanic navigation and more than 1h for the en route and terminal phases of flight."

The word outage refers to times when insufficient satellites are visible for the required integrity. These findings do not mean that GPS does not provide a position at all for these periods of outages, but it does mean that the number of satellites visible is insufficient to provide the integrity needed for a system that is the primary means of navigation. Summary: GPS-alone works, but it doesn't work well enough to be a primary means of aircraft navigation.

By analyzing the effect of adding GLONASS to GPS the following solution is offered by the study:
"Augmenting the 24 GPS satellites with the full GLONASS constellation of 24 satellites provides 100 percent availability for all modes of flight."
The following tables are taken from the study, they summarize the results for GPS-only, and for GPS+GLONASS.

FDE Availability for Oceanic, En Route, Terminal, and NPA Modes of Flight

Constellation	Oceanic (%)	En Route (%)	Terminal (%)	NPA (%)
GPS	99.00	97.77	04.97	60.12
GPS + GLONASS	100	100	100	100

Maximum FDE Outage Duration for Oceanic, En Route, Terminal, and NPA Modes of Flight

Constellation	Oceanic (min)	En Route (min)	Terminal (min)	NPA (min)
GPS	35	65	80	295
GPS + GLONASS	0	0	0	0

Summary:

- Integrity: GPS+GLONASS has enough satellites to meet the integrity requirements for primary-means navigation for aircraft; GPS-only does not.

[3] *Fault Detection and Exclusion Performance Using GPS and GLONASS*, Karen L. van Dyke. Journal of the Institute of Navigation Vol 42, No 4, Winter 1995.

Accuracy

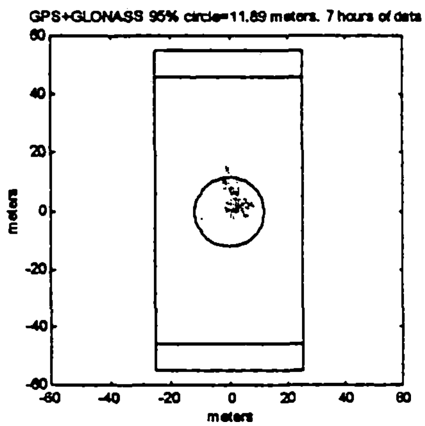
The GG24 GPS+GLONASS receiver improves accuracy over a GPS-only receiver and over a GLONASS-only receiver.

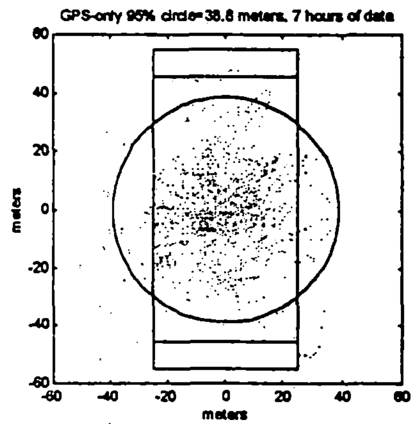
In autonomous operation, the GG24 receives and uses the signals from the GPS satellites and the GLONASS satellites. The GPS signals are deliberately degraded to give 100m position accuracy (with 95% probability). The GLONASS signals are not deliberately degraded, but are still subject to natural errors as they pass through the atmosphere. The result of combining the signals from the two systems is a position accuracy in the range of 10-15m (with 95% probability).

In differential operation the GG24 receives corrections from a differential reference station (another GG24) placed at a known point. These corrections remove the deliberate errors (on GPS) and the natural errors (on both GPS and GLONASS). This results in an accuracy of 90cm (with 95% probability). This is a similar accuracy to a state-of-the-art GPS-only system (such as the Ashtech G12). When satellite visibility is restricted then Differential GPS+GLONASS accuracy can become significantly better than Differential GPS-only because enough GPS+GLONASS satellites remain visible to keep Dilution of Precision (PDOP) low.

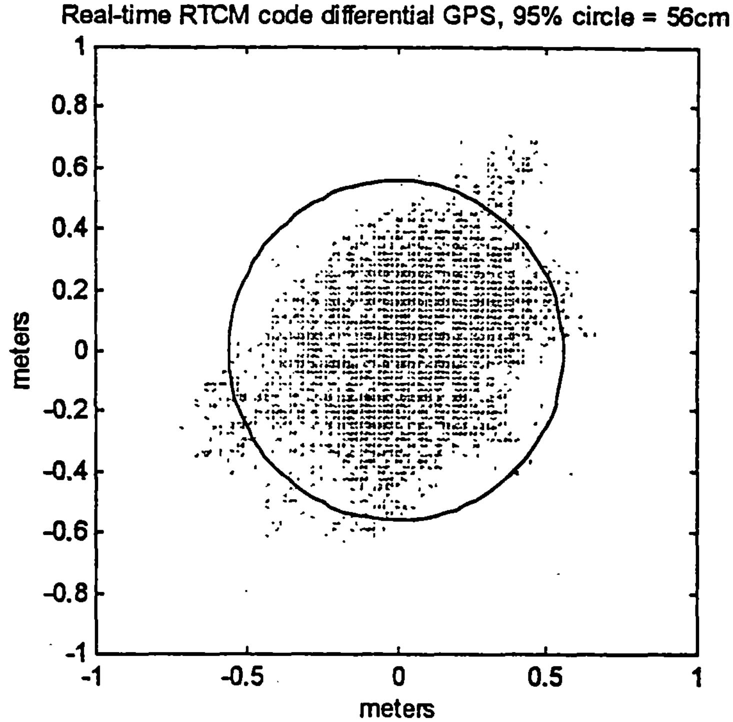
The following plots show data collected with a GG24 receiver, using both GPS+GLONASS, and data collected with a GPS-only receiver. Seven hours of data were collected, at the same time, at the same place, with both receivers. The plots show the computed position. The position has been overlaid on a (US) football field to show scale. The scatter shows the positions computed by the receivers. The center of the football field is the true position of the receiver. The circles in each plot show the radius containing 95% of the scattered positions.

The large errors on the right-hand plot are directly attributable to the degradation caused by Selective Availability. These plots show that the difference in errors is the difference between a first-down and a touch-down.





The next plot shows data collected in differential GPS mode, this shows how accuracy improves to approximately half a meter with differential corrections (Differential GPS+GLONASS accuracy is similar). Continuing the football analogy, this accuracy is about the size of 1½ footballs.



Summary:

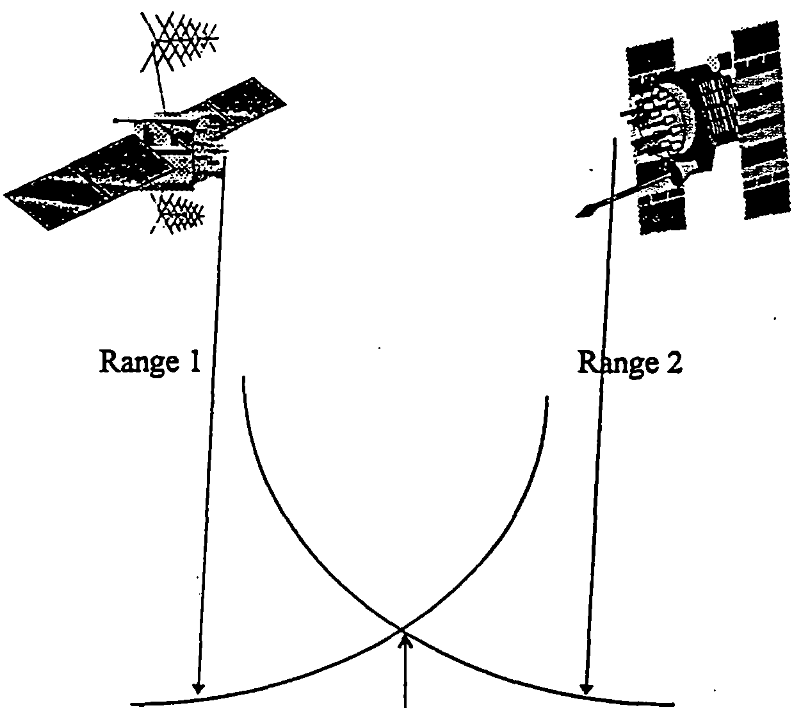
- In autonomous mode, GPS-only accuracy is guaranteed to be 100m (95%) by the policy of Selective Availability, comparable GPS+GLONASS (95%) accuracy is better than 15m.
- Differential GPS has similar accuracy to Differential GPS+GLONASS, except when visibility is restricted, when Differential GPS+GLONASS can be much better.

How GPS & GLONASS work

The basic idea, satellite ranging

Both GPS and GLONASS work on the principle of triangulation: if you know your distance from several known points, then you can compute where you are. The known points for both systems are the satellites. The signals from the satellites travel at the speed of light; the distance to a satellite is measured by timing how long the satellite signal takes to reach you; multiply this time by the speed of light and you have the distance.

time delay of signal × speed of light = distance of satellite



Intersecting ranges from known points tell you where you are

The big technical problem here is that this basic principle requires very accurate clocks, since light travels rather fast (in fact it takes only about 0.06 seconds for the satellite signals to travel to earth). The technical timing problem is overcome in each satellite system by having very precise atomic clocks, which are all synchronized with each other to nanosecond accuracy (0.000000001 seconds). These clocks cost over $100,000 each, and each satellite has four on board. So how do you use the system without spending $100k on a clock? The answer is: you don't need an expensive clock in your receiver, and here's why:
A GPS receiver has a low-cost quartz clock inside. This clock introduces an error when the measurements are made, *but* the error can be calculated and removed because the satellite clocks are precisely synchronized. To calculate latitude, longitude, altitude and the receiver clock error,

at least four satellites are needed. This is an old mathematical exercise of *solving four unknowns with four equations.*

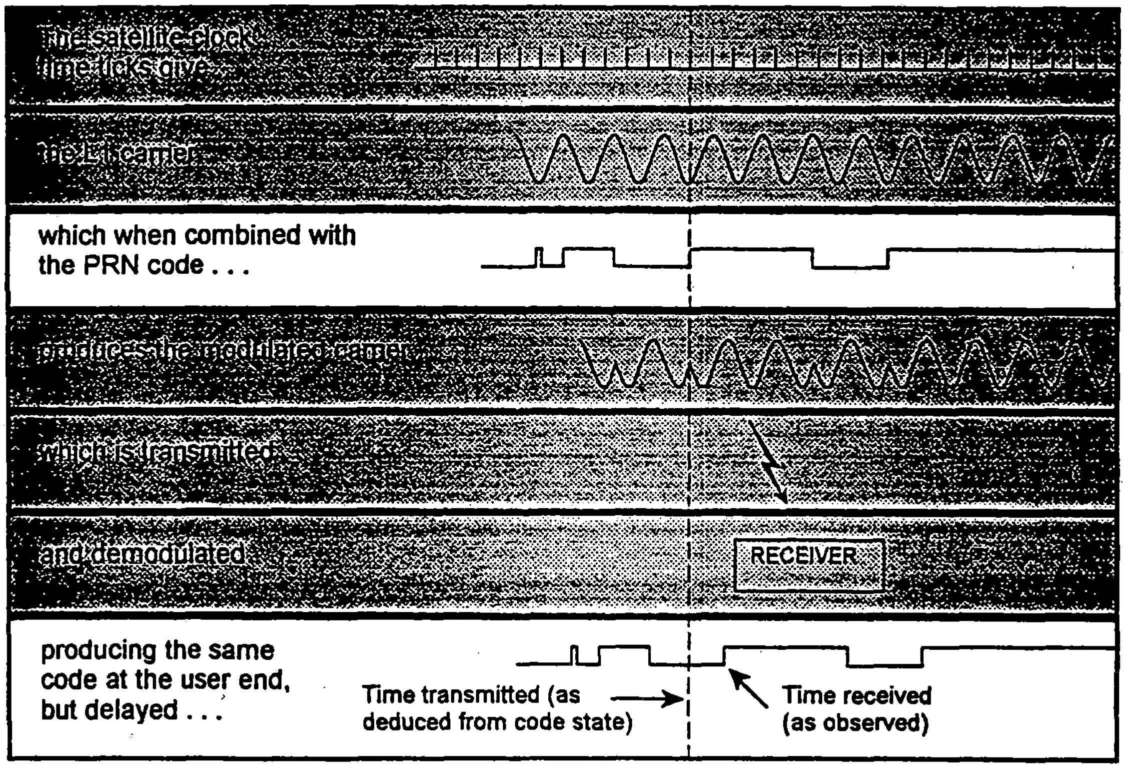
What about GPS+GLONASS?
As we've said, the GPS satellite clocks are all synchronized. Similarly the GLONASS satellites are all synchronized with each other, but GPS time is not synchronized with GLONASS time. So now the receiver clock has two errors: the error with GPS time, and the error with GLONASS time. These two clock errors, plus latitude, longitude and altitude give 5 unknowns, which are solved by having 5 satellites (or more) in view.

Summary:

- We determine our position by knowing our distance from other known positions.
- We measure the distance of the satellites by timing the delay of the transmitted signals and then multiplying by the speed of light.
- The satellites have extremely expensive and accurate clocks. Receivers do not need expensive clocks, but they do need:
  At least 4 satellites in view for a GPS-only receiver
  At least 5 satellites in view for a GPS+GLONASS receiver

Signal structure, how the time delay is actually measured

In the previous section we showed how positions are determined by measuring time delays of the transmitted signals, but how do receivers actually measure this delay?
Both the GPS and GLONASS satellites transmit a signal known as a PRN code (Pseudo Random Noise). This code is chosen for its good robustness to interfering signals. The code is a sequence of one's and zero's. The code is actually transmitted through space by modulating it onto a carrier wave. The carrier wave is a sinusoidal signal. If you could hear it, it would sound like a high pitched single tone. Every time the PRN code changes from a one to a zero (or back) the carrier wave is flipped through 180°. This is known as modulation and is shown in the figure below. The modulated carrier travels through space and, after about 0.06 seconds reaches the earth.
The GPS+GLONASS receiver has the PRN codes programmed in its memory. The receiver reproduces the PRN codes of the satellites in view, and moves them until they match the received signal. By knowing how much the code had to be moved, the receiver knows the transmission delay.



Summary:

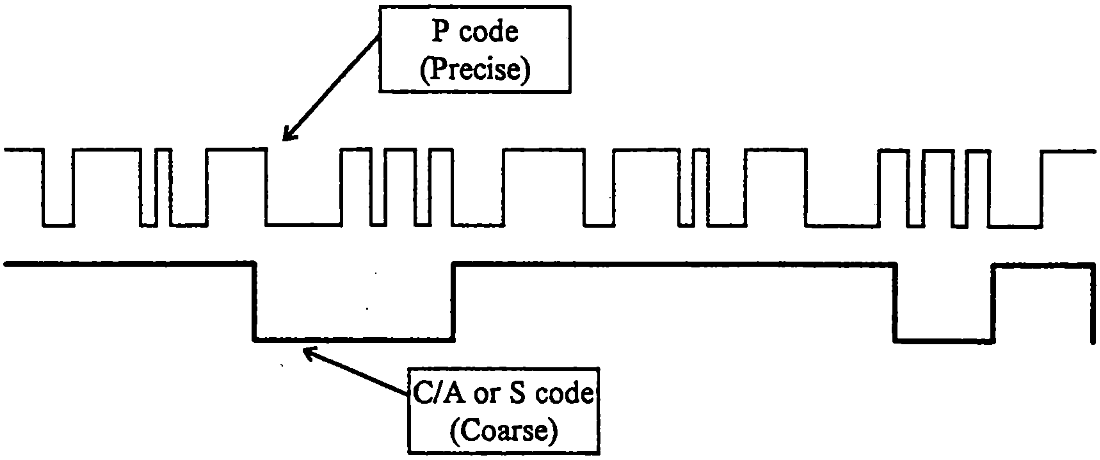
- The satellites generate known codes which are transmitted on a carrier wave.
- The receiver duplicates the code and, by matching it with the (delayed) code from the satellite, determines the time of the delay.

Signal structure, technical details

The GPS and GLONASS have a very similar signal structure.

- Both transmit on two frequency bands, called L1 and L2.
- Both have PRN codes in the L1 frequency band, known as Coarse/Acquisition (C/A) code for GPS and standard (S) code for GLONASS
- Both have more accurate PRN codes, known as Precise (P) code on both L1 and L2 frequencies.
- Both transmit almanac and ephemerides at a data rate of 50bps.

PRN codes. The P code is more precise because the rate at which zeros and ones occur is 10 times faster than the C/A or S code (for both GPS and GLONASS):



Try measuring the dimensions of this piece of paper using two rulers: one with ten times greater resolution on the tick-marks than the other and you will see why P code is more precise.

Both GPS and GLONASS have PRN codes that repeat every 1 millisecond (Called C/A for GPS and S for GLONASS).

The difference between GPS and GLONASS signal structure is that GPS uses the same frequencies but different PRN codes for each satellite (this is called CDMA, Code Division Multiple Access). GLONASS uses the same PRN codes for each satellite, but different frequencies within the L1 and L2 bands (this is called FDMA, Frequency Division Multiple Access).
GPS satellites are usually identified by their PRN codes, since they are all different. GPS PRN codes are numbered from 1 through 32, 24 of these are used for the full constellation. GLONASS satellites are usually identified by their orbital slot-number. There are 24 orbital slots, numbered sequentially 1 through 24. The satellite takes the number of slot it occupies.

The major differences in implementation between GPS and GLONASS are:

1. GPS has Selective Availability on both C/A and P codes, that is, they are deliberately degraded by "dithering" the transmit time. GLONASS has no deliberate degradation.

2. GPS encrypts the P code on both L1 and L2, the encrypted code is secret. This is known as "Anti-Spoofing". GLONASS has no encryption.

Almanacs. Both GPS and GLONASS satellites transmit navigation information about the satellites in almanacs. Each satellite transmits an almanac which tells the receiver which satellites are operating and where they are. This is how the receiver knows which satellites are above the horizon. GPS satellites are identified in their almanac by their PRN numbers. GLONASS satellites are identified by their orbital slot numbers. Each slot number has an associated carrier number, this is in the almanac, and it tells the GPS+GLONASS receiver which frequency to find the satellite on.
Further details on the almanac are given in the table on page 18.

Frequency. Each GPS satellite transmits at an L1 frequency of 1575.42 MHz, and at an L2 Frequency of 1227.60 MHz.
Each GLONASS satellite transmits at an L1 frequency of 1602 + K×0.5625 MHz, and at an L2 frequency of 1246 + K×0.4375 MHz. K is the carrier number given in the almanac for each satellite. Currently K is in the range 1 through 24.

Two changes are planned for the GLONASS frequency plan:
Stage 1. Present to 1998

The carrier numbers will be assigned in such a way as to avoid the frequencies in the band 1610.6-1613.8 MHz used in Radio Astronomy. This means the carrier number assignments K=16,17,18,19,20 will not be used. To compensate for the lost frequencies, identical frequencies will be used for two satellites on opposite sides of the earth.

Stage 2. 1998 to 2005

The next generation of GLONASS-M satellites will use the carrier number assignments 1 through 12.

Stage 3. beyond 2005

The GLONASS-M satellites will use the carrier number assignments –7 through +4. Carriers 5 and 6 will be used for interaction with the ground control segment.

Any or all of these changes in frequency will have no effect on a well designed GPS+GLONASS receiver, such as the Ashtech GG24, because the capability to handle any of the carrier number assignments is built in, and the satellite almanac always tells the receiver which assignment to use for each satellite.

Ephemerides. The satellite ephemerides are like a super-almanac, they tell the receiver *precisely* where the satellite is. Each satellite (both GPS and GLONASS) transmits its own ephemerides. The GPS satellites provide their positions in terms of the WGS 84 (World Geodetic System, 1984) reference system, the GLONASS satellites provide their positions in terms of the PE-90 (Parameters of the Earth, 1990) reference system. Inside a GG24 receiver the two systems are translated to a single reference system. The user has a choice of which reference system their position is provided in.

Satellite orbits, technical details

The orbits of GPS and GLONASS are very similar. GPS satellites are distributed in 6 orbital planes, 4 satellites per plane. GLONASS uses 3 planes, 8 satellites per plane. The inclination of the GLONASS planes is slightly higher (64.8°) than GPS (55°). Both systems' satellite orbits are circular, and with similar radii. More details in the comparison table on page 18.

Table 1 Comparison between GPS and GLONASS systems.

	GPS	GLONASS
	signal structure	
C/A Code (L1)		
Code rate	1.023 MHz	0.511 MHz
Chip length	293m	587m
Selective Availability	Yes	No
P Code (L1 & L2)		
Code rate	10.23 MHz	5.11 MHz
Chip length	29.3m	58.7m
Selective Availability	Yes	No
Encryption (Anti-Spoofing)	Yes	No
Signal Separation	CDMA	FDMA
Carrier frequencies, L1	1575.42 MHz	$1602 + K \times 0.5625$ MHz, $K \in [-7,24]$
Carrier frequencies, L2	1227.60 MHz	$1246 + K \times 0.4375$ MHz, $K \in [-7,24]$
	satellites	
number of satellites	24	24
number of orbital planes	6	3
satellites per plane	4 (unevenly spaced)	8 (evenly spaced)
orbital inclination	55°	64.8°
orbital radius	26,560 km	25,510 km
orbital period	11^h58^m	11^h15^m
	almanac	
duration	12.5 minutes	2.5 minutes
capacity	37,500 bits	7,500 bits
	general	
time reference	UTC (US Naval Observatory)	UTC (Soviet Union)
geodetic datum	WGS 84	PE-90

GPS+GLONASS Standards

There are two standards that are used widely and successfully for GPS applications. These are the RTCM (Radio Technical Commission for Maritime Services) standard for differential corrections, and the NMEA (National Marine Electronics Association) standard for reporting position, velocity and satellite data. Although both these standards were initially for marine use, they have been adopted worldwide for all applications of GPS.

RTCM SC-104

The RTCM Special Committee 104 (SC-104) has defined differential correction messages that are used worldwide for GPS. The messages that carry the GPS corrections are message type 1, and message type 9. In 1995 the committee defined similar messages for GLONASS differential corrections, message type 31 is the GLONASS equivalent to message type 1, and message type 34 is the GLONASS equivalent to message type 9.

Other RTCM messages have information about reference station parameters and satellite health. These have been defined for both GPS and GLONASS.

Other messages are being developed to improve further the operation of GPS+GLONASS systems in differential mode. A GLONASS-GPS time offset message has been proposed, this will allow the reference station to report the time offset between the two systems so that the GPS+GLONASS receiver will not have to calculate it (see Page 14 for a discussion on time errors and how they are dealt with).

RTCM SC-104 messages for GPS and GLONASS.

	GPS	GLONASS
	Message Type	Message Type
Differential Corrections	1	31
Reference Station Parameters	3	32
Constellation Health	5	35
Radiobeacon Almanac	7	33
Partial Satellite Set Differential Corrections	9	34
GLONASS-GPS Time Offset	37	37

NMEA 0183

The National Marine Electronics Association has defined the Standard NMEA 0183 for interfacing marine electronic devices. Six messages have been defined specifically for GPS use, these are:

GGA Global Positioning System Fix Data
GSA GPS DOP and Active Satellites
GSV GPS Satellites in view
GRS GPS Range Residuals for each Satellite
GST GPS Pseudorange Measurement Noise Statistics in the Position Domain
GBS GPS Satellite Fault Detection with Estimated Bias Statistics

A proposal is currently under review by the committee to determine how to incorporate GLONASS satellite information as well.

How GG24 Works

Ashtech's GG24, is the world's first fully integrated GPS+GLONASS receiver. GG24 is available on a single OEM Board or in a compact packaged sensor format, for easy integration with electronic displays, vehicle tracking, flight management, survey and mapping systems.

Navigation Modes (Availability & Accuracy)

The GG24 has 12 parallel channels for tracking GPS satellites, and 12 parallel channels for tracking GLONASS satellites. With this capability, the GG24 will always use the best available constellation to provide the most accurate position.

- The greatest accuracy is obtained when differential corrections are available for both GPS and GLONASS satellites. The GG24 can be used as a reference station to generate RTCM corrections for GPS and GLONASS, and a GG24 can use RTCM corrections for both systems.
- If differential corrections are available for only one satellite system (either GPS or GLONASS) then the GG24 will automatically use only those measurements for which it has corrections.
- If GG24 has no differential corrections at all, then it will automatically use all available healthy satellites, from both constellations, to compute a position.
- If one satellite system is shut down or jammed, or if satellites become unhealthy (generating incorrect data), the GG24 will automatically use the satellites which are operating correctly.

The GG24 uses the information in the satellites almanacs, as well as built in RAIM (Receiver Autonomous Integrity Monitoring) to determine which satellites are healthy.

GG24 Navigation Modes

Available Constellation	GG24 Mode	Typical Horizontal Accuracy expected[4].
Differential GPS & Differential GLONASS	DGPS & DGLONASS	35cm
GPS & Differential GLONASS	DGLONASS	1m
GLONASS & Differential GPS	DGPS	40cm
GPS & GLONASS	GPS & GLONASS	7m
GLONASS	GLONASS	8m
GPS	GPS	25m

[4] Differential GPS accuracy is affected by the radio data rate. If the data rate is slow then SA causes errors to grow while the corrections are being transmitted. Both Differential GPS and Differential GLONASS accuracies are affected by the distance between the reference station and the rover. The longer the distance, the worse the accuracy. The accuracy shown was measured in tests of the GG24, with a short baseline between reference and rover, radio data rate 300bps, HDOP<4.

RAIM (Integrity)

GG24 implements the Receiver Autonomous Integrity Monitoring (RAIM) required for En Route, Terminal and Non-Precision Approach stages of flight. The RAIM alarm limit may also be set by the user to suit other applications. The RAIM algorithm will detect and remove erroneous measurements. A study by the DOT Volpe center (See Page 9) shows that the availability of RAIM for these stages of flight is 100% using GPS and GLONASS (availability of RAIM means that there are enough satellites visible to perform the Integrity monitoring). If for any reason RAIM is not available at any time (e.g. if too many satellites become blocked), the GG24 will tell you.

Size, weight & power consumption

The GG24 is available in two different formats

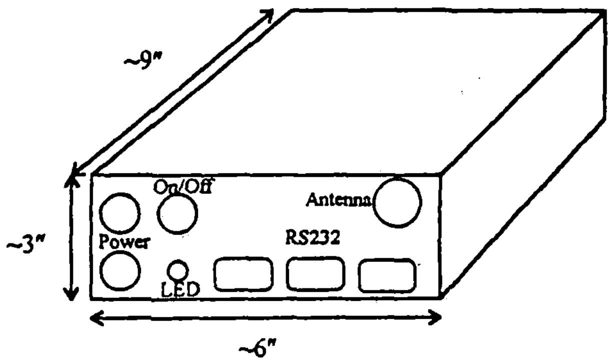
1. OEM Board, Eurocard Format
2. Sensor, with power supply and internal PCMCIA memory card

The OEM Board

- Standard Eurocard format:
    - Size 16.7×10.0cm.
    - Connector DIN64.
- 2 RS232 Serial ports.
- Power 5 VDC ± 5% input, 1.8W.
- Weight 6oz.

GG24 Sensor:

- Aluminum housing.
- Meets MIL-Spec 810 E standards for wind-driven rain and dust.
- 3 RS232 Serial ports.
- Optional internal radio for differential corrections.
- Internal PCMCIA memory card up to 40Mbytes.
- Power supply, 6-15 VDC input, <3W.
- Weight 5 pounds.



More information on Ashtech, GPS, and GLONASS can be found on the World Wide Web:

Ashtech	www.ashtech.com
GPS: US Coast Guard Navigation Center	www.navcen.uscg.mil/gps/gps.htm
GLONASS: Coordinational Scientific Information Center of Russian Space Forces.	www.rssi.ru/SFCSIC/glonass.html

DIFFERENTIAL GPS: AN AID TO POSITIVE TRAIN CONTROL

Report to the Committees
on Appropriations

Federal Railroad Administration

Office of Policy
Office of Railroad Development
Office of Safety

June 1995

U.S. Department of Transportation
Federal Railroad Administration

Office of the Administrator

400 Seventh St., S.W.
Washington, D.C. 20590

JUN 29 1995

The Honorable Mark O. Hatfield
Chairman, Subcommittee on Transportation
and Related Agencies
Committee on Appropriations
United States Senate
Washington, D.C. 20510

Dear Mr. Chairman:

Enclosed is a report in response to the Appropriations Committee's request in Senate Report 103-310 accompanying the Department of Transportation and Related Agencies Appropriations Act, 1995. The Committee directed that a report be submitted "on the benefits, costs, desirability, feasibility and implications of using current and planned differential global positioning systems (DGPS) as a means of further promoting the accuracy and utility of positive train control systems." The Department's Federal Railroad Administration (FRA) is responding to that request.

During the preparation of this report, FRA continued discussions with railroads, other modal administrations within the Department of Transportation, and the U.S. Army Corps of Engineers. The results of these discussions are elaborated upon in the report. We conclude that DGPS, both current and planned, could satisfy the Location Determination System requirements for the next generation positive train control systems.

On behalf of FRA, I am pleased with the very encouraging vision for the future outlined in this report.

An identical letter has been sent to Chairman Wolf.

Sincerely,

Jolene M. Molitoris
Administrator

Enclosures

cc: The Honorable Frank R. Lautenberg

EXECUTIVE SUMMARY

The report of the Senate Appropriations Committee on the Department of Transportation and Related Agencies Appropriations Bill, 1995, directed the Federal Railroad Administration (FRA) to submit a report regarding the benefits, costs, desirability, feasibility and implications of using current and planned "differential GPS" as a means of promoting the accuracy and utility of positive train control systems. Positive train control systems are technologies having the capability of preventing collisions between trains, avoiding overspeed derailments, and providing other safety and economic benefits.

The Global Positioning System (GPS) data available to civilian users is not sufficiently accurate to meet the safety-related needs of transportation users. The United States Coast Guard is deploying a differential correction service for GPS to enable precision navigation in harbors and inland waterways. Railroads are exploring use of this differential GPS service as a location determination system in emerging communication-based train control systems.

FRA strongly supports development and implementation of communication-based positive train control systems. Such systems have the potential to significantly enhance railroad safety and to provide many additional benefits, including full exploitation of potential line capacity by freight and passenger railroads. Such systems can also lower the cost of train control for new high-speed rail service.

The two primary train location systems that have been actively considered for use in communication-based train control systems are based on differential GPS and transponders. North American railroads are exploring use of both of these location determination systems. At the present time, differential GPS appears to have the advantage of lower initial cost (e.g., all necessary hardware can be placed on the locomotive) and less maintenance (e.g., transponders can be damaged by vandalism or routine track work). The Burlington Northern Railroad and the Union Pacific Railroad have joined together to develop a Positive Train Separation (PTS) Pilot Project on their lines in the States of Washington and Oregon that will employ differential GPS as the primary location determination system.

Differential GPS will soon be available to marine users all along the U.S. coast line and throughout our principal inland waters. With an incremental expenditure of less than $25 million, sufficient additional transmitters could be placed to provide total coverage of the 48 contiguous States. This highly accurate location determination system could then be used by both rail and highway users, among others. Public deployment of differential GPS will be necessary if this system is to be used by railroads. Private differential services do not offer high reliability, consistent protocols and full land area coverage--attributes that are essential to interstate rail movements employing interoperable train control systems.

Implementation of communication-based positive train control can prevent accidents and casualties valued at approximately $35 million per year. However, the initial costs of positive train control systems for U.S. railroads may approach over $800 million. In addition to equipping trains with location systems, positive train control will require the use of on-board computers, extensive data bases, data radio systems along the principal rail lines, and development of complex on-board and "central office" software. These are costs that private railroads will shoulder to the extent they are convinced that adequate business benefits will result. The Union Pacific/Burlington Northern PTS Pilot Project is persuasive evidence that emerging business needs and maturing technology will converge, leading to the requisite private investments.

Non-safety benefits of positive train control may include better quality service and more efficient equipment utilization through closer tracking of car movements, reduced fuel consumption through pacing of trains, and more effective use of existing infrastructure that effectively increases the capacity of the railroad. Public passenger service providers that operate over freight railroads would also benefit from the capacity and safety benefits of this kind of technology. Over time, intermodal applications of communication-based technology could link highway-based intelligent transportation systems with positive train control systems to yield synergies such as improved safety at highway-rail crossings.

In summary, full deployment of U.S. Coast Guard differential GPS can significantly aid the development of positive train control systems by providing an affordable and competent location determination system that is available to surface and marine transportation throughout the contiguous United States.

Report of the Federal Railroad Administration to the Appropriations Committees:

Use of Differential GPS to Aid Positive Train Control

1.0 Direction

The Report of the Senate Appropriations Committee on the Department of Transportation and Related Agencies Appropriations Bill, 1995 stated as follows:

> The Committee supports the current activities within the Department to utilize differential global positioning systems (DGPS) as a means of promoting surface transportation safety and technology. As part of DOT's examination of the potential uses of this technology, the FRA is directed to submit a report to the House and Senate Appropriations Committees by May 1, 1995, on the benefits, costs, desirability, feasibility, and implications of using current and planned DGPS as a means of further promoting the accuracy and utility of positive train control systems.
>
> (Senate Report No. 103-310 at 147.)

This report responds to the Committee's direction.

2.0 Background

Over the past decade, the Federal Railroad Administration (FRA) has supported the railroad industry's effort to develop advanced technology for the control of train movements and the integration and use of information pertinent to train operations. During this effort, FRA has participated in evaluation committees and has collaborated with all parties involved to identify and address obstacles to this development. More recently, FRA promoted deployment of next-generation train control technology through roundtable discussions with industry, labor, suppliers, and other DOT agencies as part of the Federal Railroad Administrator's outreach program. The initial phases of this effort were detailed in FRA's report to the Congress pursuant to section 11 of the Rail Safety Enforcement and Review Act, "*Railroad Communications and Train Control,*" ("*Train Control Report*"), dated July 8, 1994.

As noted in the *Train Control Report*, the industry is on the threshold of developing and deploying a family of technologies or systems that can provide for **positive train control (PTC)**. PTC systems are those train control systems that can prevent main line collisions and overspeed derailments, and provide enhanced protection for personnel and equipment working on or adjacent to the track structure. The goal of providing for positive train separation is embodied in one of the "Most Wanted" safety recommendations of the National Transportation Safety Board. Enhanced versions of PTC systems can expand the effective capacity of the railroad and make it more efficient by providing for flexible, moving blocks[1] and precise planning and execution of optimized train operations.

Over the past several decades, the energy efficiency and congestion mitigation potential of railroad transportation has significantly increased the demand for and use of the railroad infrastructure of the United States. Private sector rail service providers have been under increased pressure to address capacity constraints to meet this increased demand.

In 1994, the Burlington Northern and Union Pacific railroads (BN/UP) in a joint project initiated the development of a prototype **Positive Train Separation (PTS)** system to reduce the risk of accidents as well as to provide a foundation for future productivity improvements in the freight railroad industry. The PTS implementation approach is a successor to the freight railroad industry **Advanced Train Control System (ATCS)** project on which major development efforts have been underway for over ten years.

The initial PTS prototype operation is planned for over 800 miles of trackage in the states of Washington and Oregon with testing to begin in 1995 and to be completed in 1996. This project has been endorsed by the Board of Directors of the Association of American Railroads and will serve as a prototype for development of specifications ensuring interoperability among PTC systems nationally. Successful demonstration of PTS is expected to lead to future enhanced PTC applications under which trains would be guided by computer-assisted precision movement plans thereby improving the flow of traffic and optimizing rail plant capacity.

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[1]Conventional railroad signal systems divide the track into fixed "blocks" between wayside signals. Block lengths are established based upon the maximum stopping distance of long, heavy trains operating at maximum authorized speeds. Operations must be restricted both in the particular block occupied by a train and in at least one adjacent block. Contemporary communication-based signal systems will be capable of defining flexible or moving "blocks" (track segments restricted for exclusive use of the train in question) based on actual train speed, direction of movement, and stopping characteristics. Flexible or moving blocks allow more efficient use of the railroad by increasing the number of trains than can be operated within a given time period.

The FRA, as part of the Next Generation High-Speed Rail Program, is sponsoring the development of **High-Speed Positive Train Control (HSPTC)** systems to enable implementation of high-speed rail service in selected corridors on existing track infrastructure, which is often shared with freight railroad carriers. When high speed service is provided on a route, all operating locomotives and control cars must be equipped with train control apparatus. The initial demonstration of HSPTC is targeted at a 44-mile stretch of track in Michigan in 1996. The Michigan project will be coordinated with the UP/BN pilot to ensure interoperability.

The basic technologies employed in both of these train control systems can be summarized as follows. Each controlling locomotive will be able to automatically determine its position and will be able to communicate its position and receive instructions automatically by digital radio. The locomotive will be equipped with onboard computer processing capability and a route database. The onboard processor will receive and store instructions with respect to the permitted operating limits and conditions, and the processor will automatically apply the train brakes to safely stop the train if it determines that authorized location permission or speed authorities will be exceeded.

In the past, highly effective automatic train control (ATC) systems have relied upon track circuits for train detection and a limited set of codes sent through the rail to provide cab signal indications. Such systems commonly provide only four indications. These systems are very safe and reliable; but they have limited functions, require fixed blocks (i.e., rigid segmentation of track rather than flexible blocks tailored to particular train movements) and have a high cost to install and maintain. New PTC systems will be communication-based. That is, they will depend upon use of data communication over a variety of paths, including radio, to gather information for integration by microprocessors. The communications platform used by PTC systems may also be available for a variety of other business purposes.

The basic differences between the freight industry PTS approach and the HSPTC approach lie in the degree of control exercised from a central office as compared with distributed field locations. Despite these differences in degree and near-term intent of the systems, for <u>both</u> systems *precise automatic location information is vital to their satisfactory operation.* The PTS project has termed the automatic location element of their system the **Location Determination System (LDS)**, and that acronym will be used in the remainder of this discussion.

One of the principal issues related to PTC is affordability. If systems are highly affordable, they will be widely deployed for both safety and nonsafety business purposes. Wide deployment will mean that collision avoidance and other safety features will be available over a larger portion of the national rail system. Universal equipping of trains with on-board systems will be necessary to realize maximum safety benefits. LDS must be available throughout the national rail system and be compatible with interoperable PTC systems.

3.0 Competing Technologies for Determining Train Location

Presently, there are a limited number of options for selection of a primary LDS. Although information from existing signal systems may be helpful for confirming train location, signal systems are not in place on track constituting about half of the road miles operated. Further, "block occupancy" derived from a signal system will not provide precise location within a block, speed, or direction of movement. In addition, many existing systems, or portions of them, are "automatic", i.e., operate in the field without central direction or communication--so information from them is not now available at any central location.

Two primary train location systems are currently under development for railroad use: transponders and augmented GPS.

3.1 Transponders

A transponder is a device which receives and retransmits energy. Transponders placed along the track at suitable intervals and at key locations, together with an on-board capability to read digitally encoded information provided by the transponder, is a technically viable option that has been employed in railway signaling internationally.

On the North End of Amtrak's Northeast Corridor (NEC), the existing cab signal/ATC system will be upgraded to provide additional aspects to accommodate higher speed trains as a new part of the traffic mix. An advanced civil speed enforcement system using transponders will be added to that system. Placed between the rails or adjacent to the track, passive transponders will be read by a scanner on-board the locomotive. The transponder will indicate location (including track number), upcoming speed restrictions, the location of the next transponder, and other information as desired. This information can be integrated with information in the on-board computer data base and also transmitted to a central office. Between transponders, odometer readings based on wheel rotation can be used to interpolate train location (with expected error due to wheel slip, etc., added to the safety margin). Because the NEC is electrified (or is under consideration for electrification), because an existing ATC system is in place along the length of the corridor, and because the bulk of the rail equipment operating there is dedicated to that service, the election of transponders for civil speed enforcement and positive stop features on the NEC will not have precedential value for the rest of the United States.

Transponders were also selected as the LDS for the Association of American Railroads/Canadian Railways ATCS specifications, which are now being superseded for U.S. operations by the UP/BN PTS project. ATCS transponders are based on different technology than the European transponders that will be employed on the NEC. Thus, the NEC system will not serve as a valid test of the specific transponder technology that had been under most active consideration for the bulk of the North American freight system. However, the two major Canadian railroads (CN North America and the CP Rail System) continue to experiment with ATCS-compliant transponder systems. There is presently no reason to believe that significant technical problems will be presented.

3.1.1 Transponder Costs

Overall cost for a transponder-based location determination system applied to the U.S. main line rail system could be slightly greater than $200 million. Of that, perhaps $180 million might be required for purchase and installation of on-board readers (scanners) for as many as 18,000[2] locomotives. Approximately $20 million might be required for purchase of transponders, and additional cost would be incurred in placing them along the track structure. Annual maintenance costs would be incurred that FRA cannot estimate at this time. It should be noted that railroads are concerned that transponders will be subject to damage from production track work, dragging equipment and other causes. Some cost would be incurred to reprogram transponders as circumstances change in the field.

The costs quoted above do not include other necessary components of a PTC system, such as wayside data radios, on-board transceivers and computers, and extensive software and databases. Costs and benefits of PTC systems were estimated in FRA's Train Control Report.

3.2 Global Positioning System (GPS)

Properly "augmented" by a means of correcting small inaccuracies in GPS location data, GPS offers a train location system well suited to operations over the greatest portion of the national rail network. No fixed wayside infrastructure is needed to interface with the on-board equipment. GPS satellite signals are available throughout the United States.

GPS is a space-based radionavigation system which is managed for the Government of the United States by the U.S. Air Force, the system operator. GPS was originally developed as a military force enhancement system and will continue to fill that role. However, GPS also has significant potential to benefit the civil community. In an

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[2]Estimates provided are maximums. For instance, it is likely that railroads would not elect to equip all locomotives with on-board systems. Rather, something more than half of the road locomotives (perhaps 8,000 units) would likely be designated as lead units.

effort to make GPS service available to the greatest number of users while ensuring that national security interests are protected, two GPS services are provided. The Precise Positioning Service (PPS) provides full system accuracy to U.S. and allied military users. The Standard Positioning Service (SPS) is designed to provide a less accurate positioning than PPS for civil and all other users throughout the world.

System accuracy for the SPS user is maintained at a lower level than the PPS user through the use of Selective Availability (SA). SA is the means by which the U.S. intentionally degrades full system accuracy to an unauthorized user (i.e., SPS user). SA was developed by the U.S. to ensure that an adversary does not use GPS as a military force enhancer against the U.S. and its allies.

SPS is the standard specified level of positioning accuracy that is available, without restrictions, to any user on a continuous worldwide basis. The accuracy of this service is established by both DOD and DOT based on U.S. security interests. This specification states that at a minimum, the SPS user is guaranteed a predictable positioning accuracy of 100 meters (with 95% reliability). Further background and description of GPS and augmentations may be found in "*The Global Positioning System: Management and Operation of a Dual Use System: A Report to the Secretaries of Defense and Transportation*" (Joint DOD/DOT Task Force; December 1993), copies of which are provided for the Committees' files.

Trains and other transportation vehicles will depend upon frequent updates of positioning information. The rate of data transmission for GPS and augmentation systems such as the Coast Guard system described below is adequate to support train control systems. Loss of signal is not expected to be a significant problem. In unusual situations, such as tunnels, locomotive odometer readings can be used to interpolate in the same manner as with transponders.

3.2.1 Differential GPS and the PTC Pilot Projects

As noted above, the civilian or SPS form of GPS has limited accuracy in normal service and is subject to further degradation in times of national emergency. The SA technique is capable of degrading system accuracy by several kilometers or more, as demonstrated in tests conducted by the DOD. These limitations render unaugmented GPS unacceptable as an LDS for train control purposes. However, GPS as augmented with a differential correction system (DGPS) appears to have great promise for performing well as a primary LDS for use in PTC systems.

The first general deployment of DGPS is being undertaken by the United States Coast Guard through local area systems (LADGPS) to provide for harbor and inland waterway navigation. This system will blanket the coasts and major river systems, leaving gaps inland, particularly in the western States. The U.S. Army Corps of

Engineers is also planning certain inland radio sites using USCG standards and frequencies.

As noted above, the Burlington Northern Railroad and the Union Pacific Railroad have been jointly developing a pilot project to demonstrate a PTS system (a first-generation communication-based PTC system). The railroads and their suppliers have evaluated their requirements for train location in relation to the Coast Guard's LADGPS system as follows:

- The single most stressing requirement for the location determination system to support the PTS system is the ability to determine which of two tracks a given train is occupying with a very high degree of assurance (an assurance that must be greater than 0.99999 or (0.9_5)). The minimum center-to-center spacing of parallel tracks is 11.5 feet. Direct GPS *will not* satisfy this requirement. The USCG LADGPS radio tower beacon system, as a first level of augmentation, also *will not* satisfy this requirement. When viewed as a two dimensional area problem, it is unlikely that *any* economically feasible system could achieve this accuracy to the required 0.9_5 probability.

- However, fortunately, the nature of the train location problem is more *one* dimensional, with well defined discrete points (switches) where the potential for diverging paths exists. The USCG LADGPS narrows the location to less than 10 meters (33 feet). The most frequent interval at which successive turnouts can be located (locations at which a train may diverge from its current route over a switch) is 48 feet. Since the train is constrained to be *located on a track*, as opposed to somewhere within an area, this collapses the problem from a two- or three-dimensional problem into a *one*-dimensional problem.

- The *detailed* track geometry data for a specific route are stored on-board the locomotive (needed for calculating the safe braking distance algorithm). Which of two parallel tracks a train is occupying can then be determined by maintaining a continuous record of which direction the train took over each diverging switch point (normal or reversed). There are several heading reference system techniques available to make this determination. Although the final design and choice have not been concluded, they will be sometime between fourth quarter 1995 and mid-1996. DGPS is also proposed as the train location system for the FRA-sponsored HSPTC system.

This analysis supports the utility of DGPS, supplemented by other techniques, to determine train location with a very high degree of confidence.

3.2.2 DGPS Cost Considerations

The cost of equipping 18,000 locomotives with a GPS receiver, a differential beacon receiver, and appropriate antennas could be on the order of $2,000 per unit or $36 million total. Annual maintenance cannot be reliably estimated at this time. No fixed infrastructure would be required along the right-of-way.

As discussed below, use of DGPS as the primary location determination system with a PTC system is practicable only if GPS and DGPS services are available with a high degree of reliability throughout the contiguous 48 States.[3]

Again, the costs quoted above do not include other necessary components of a PTC system, such as wayside data radios, on-board transceivers and computers, and extensive software and databases.

4.0 Public Sector Role in Location Determination: The Future of Augmented GPS

The Department of Transportation and the Department of Defense are working in partnership to identify an appropriate strategy for civilian use of GPS, supported by the National Telecommunications and Information Administration (NTIA), Department of Commerce. Recently the Government agencies prepared "*A Technical Report to the Secretary of Transportation on a National Approach to Augmented GPS Services*" (NTIA Special Publication 94-30; December 1994) ("DOT/NTIA Report), copies of which are provided with this report for the Committees' files. The DOT/NTIA Report detailed available options for providing location determination systems that can serve the public, including all major forms of transportation, well into the next century. The report made eight recommendations, two of which follow:

- DOT, in coordination and cooperation with the Department of Commerce, should plan, install, operate, and maintain an expanded low frequency/medium frequency beacon system modeled after the USCG's LADGPS system to provide nationwide coverage for land and marine users.

- DOT, in conjunction with other Federal agencies, should coordinate the implementation, operation, and maintenance of all Federally-operated augmented GPS systems to insure optimal use of resources by maximizing commonality of system components.

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[3]Since locomotives do not move between points in the contiguous States and Alaska, train control for the Alaska Railroad presents a special case that would warrant separate analysis.

DOT, in conjunction with other agencies, is further reviewing the DOT/NTIA Report prior to deciding what system to implement and recommending how to implement it.

4.1 U.S. Coast Guard (USCG) DGPS

Based upon a review of civilian sector needs, the DOT/NTIA Report recommended consideration of two architectures, both of which would rely upon USCG's LADGPS to provide nationwide coverage for marine and land users.

As noted above, the Coast Guard is already deploying LADGPS for harbor and inland waterway navigation. The 61 radiobeacon transmitters of the LADGPS system will be in place by January 1996 at a cost of $17.2 million, plus $5.0 million in maintenance annually. The DOT/NTIA Report estimates that expansion of the LADGPS for universal coverage of the contiguous 48 States would require 20 to 50 additional sites at an initial cost that should not exceed $25.0 million with annual maintenance that should not exceed $4.0 million. These costs depend on engineering development that is yet to be completed. The incremental cost of providing complete coverage for land users will be reduced to the extent that the U.S. Army Corps of Engineers establishes USCG-specification LADGPS radiobeacons for its own purposes. As discussed below, the cost might be further reduced through public-private partnerships that provide sites and access to necessary infrastructure.

As discussed above, the BN/UP project and the Michigan HSPTC demonstration will both utilize GPS, corrected by the USCG DGPS system as the primary location determination technology for their PTS pilot project. Initial demonstration of positioning is expected during 1995, and testing and evaluation will be completed by the end of 1996.

4.1.1 Public/Private Partnerships in Deployment of DGPS

Railroads operate one of the most extensive telecommunication networks in the United States, with transceiver base stations placed at over 16,350 locations throughout the Nation. Most of these sites are privately owned by the railroads. This communication infrastructure is necessary to support safe and efficient rail transportation. Railroads pay to acquire, install and maintain this infrastructure and support the work of the Association of American Railroads, which coordinates frequency allocation in the Railroad Radio Service. Railroads also pay licensing and other fees to the Federal Communications Commission.

The costs of deploying and maintaining USCG LADGPS radiobeacons include site acquisition, security and provision of electrical power. Preliminary discussions between the Coast Guard and freight railroads suggests that opportunities may exist for co-location of LADGPS transmitters with railroad radio base stations at reduced cost to the Government over other alternatives. Freight railroads have indicated to FRA that they would welcome the opportunity to cooperate in filling in the gaps in DGPS which would benefit all of surface transportation.

4.2 FAA Options for Augmentation of GPS

The Federal Aviation Administration (FAA) has also announced a major commitment to use of augmented GPS systems for aviation navigation requirements, including precision approaches. The FAA has developed a Wide Area Augmentation System (WAAS) for aviation use of GPS. This system is not as well suited for train control as is the USCG LADGPS because of terrain masking of the geostationary satellites in many areas where trains must travel.

4.3 Private DGPS Services

The essential technical requirement for the provision of any DGPS service is a one-way communication link which transmits the correction signals to the user from the known location where the correction quantities are generated. Typical DGPS corrections services now being offered utilize data radio, but could easily be sent by wire telephone line or by fiber optic cable. By radio, differential correction signals are transmitted in digital data form using any one of several protocols, provided that the transmitter and receiver are coordinated as to frequency and data protocol.

One radio communication link now occasionally used for DGPS is a "subcarrier" channel of a commercial FM broadcast station. The FM modulation method permits the simultaneous broadcast of program material on one or more subcarrier channels in addition to the main program, at the option of the station licensee. These operations are regulated by the Federal Communications Commission (47 CFR 73.319) on the 100 channels allocated to the FM broadcast service.

Subcarrier transmissions typically cover about the same 45-mile radius from the antenna as the main broadcast channel. Proprietary data and programming coding methods are used to assure that only subscribers have access to the subcarrier program information. Some FM broadcast stations now provide DGPS services via subcarrier channels, using a variety of proprietary data formats. Each such station uses its own proprietary equipment to generate the DGPS correction factors and broadcasts them on its own frequency to its assigned coverage area. Such services can be very useful to localized users, such as land surveyors, who routinely operate in a single metropolitan area and can establish a single commercial relationship with a local DGPS service provider. Such users might want or need to access only one to three DGPS services to assure full reliable coverage of their working territory, even in a very widespread metropolitan area such as Los Angeles.

However, according to the DOT/NTIA report, even maximum implementation of DGPS via FM broadcast subcarrier would likely fail to cover significant portions of the land area of the western United States, where FM broadcast stations do not now provide full coverage. In addition, the reliability, dependability, and continuity of DGPS service would depend on the equipment and maintenance provided by each local broadcast station licensee, not only for the broadcast transmitter equipment but for the precision differential correction signal generating equipment as well.

For a wide-ranging mobile user, even assuming total national FM subcarrier coverage, a receiver frequency change would certainly be needed and a digital protocol change would not be unlikely each time a user passed from one broadcast station coverage area to another (approximately every 90 miles, or, for instance, every hour for an Amtrak train crossing Kansas at 90 mph.) At each service boundary, the user would either need to know the new frequency, or lose DGPS service until the new source of correction signals could be sought out by testing all of the available FM broadcast frequencies. At best, this kind of administrative infrastructure would be extremely cumbersome.

If PTC systems are to be implemented, railroads will require an effective location determination system which is consistently available across the national rail system. Major gaps in geographic coverage will be unacceptable. Railroads operate in many remote and sometimes sparsely populated areas; in these areas "terrain masking" poses a substantial problem. This terrain masking also inhibits the "line of sight" reception of FM subcarrier broadcast signals in rural areas, as well as those from commercial satellite DGPS providers. Service dependability and reliability must be of the highest order, and any local service failures would result in slowing or stopping rail traffic over widespread areas. For any GPS-based location system, a standard frequency and data format protocol will enormously facilitate implementation of the train control system and will avoid the necessity for multiple DGPS receivers and/or multiple protocols.

Railroads provide service over a national system of some 150,000 road miles. Locomotives now often operate in "pools", and accordingly, operate over wide areas on lines of multiple carriers, often as the controlling lead locomotive. Interoperability of on-board train control equipment will be essential for the railroads to realize the safety benefits of the new positioning technology. It is clear that any augmentation approach that requires onboard receivers to utilize multiple frequencies and to interpret signals encrypted using a variety of proprietary protocols would materially drive up the cost of onboard systems.

Requiring railroads to subscribe to private FM subcarrier services on up to 100 different FM frequencies to cover each broadcast service market would itself add unreasonable continuing expense and administrative burden and thus deter implementation of PTC systems. Since all markets presently served by subcarrier FM services are local, there is no basis to estimate potential costs of such service to railroads (which would require high-reliability continuous service to thousands of mobile units at any given time.)

Use of FM subcarrier transmission of DGPS correction signals is eminently suitable for local users. However, this transmission method is unsuitable to operate mobile units on a nationwide basis.

5.0 PTC Costs and Benefits

As noted above, our national investment in LADGPS has already been substantially committed. Implementation of the U.S. Coast Guard LADGPS will support safe and efficient marine navigation in our harbors and inland waterways for decades to come. A further initial investment of less than $25 million can fill in the gaps in coverage across the contiguous United States. This LDS will then be available to aid the safety and efficiency of interstate commerce by highway and rail, as well.

If LADGPS is completed as a LDS available to surface transportation, railroads could make extensive use of DGPS at an initial cost for the LDS alone of less than $40 million. In the Train Control Report, FRA has estimated that collision and overspeed railroad accidents cost the Nation approximately $35 million *per year*. Were LADGPS a complete train control system, the costs of completing the system would be recovered in less than two years based on this application alone, even accounting for reasonable maintenance expense.

Of course, an LDS would be only one element of a complete communication-based train control system. In order to test their PTS technology in the Pacific Northwest, for instance, the Burlington Northern and Union Pacific are putting in place a data radio system all along their rights-of-way, equipping locomotives with on-board computers and custom software, developing data bases that describe in detail the entire railroad territory, developing office software than can communicate with existing computer-aided dispatching systems, and working intensively with other railroads and FRA to ensure that the completed system will have the capability to be interoperable with other train control systems developed in the future.

The Association of American Railroads has estimated that development and deployment of communication-based PTC throughout the industry could cost over $800 million, before expenses for maintenance. Obviously, these costs cannot be justified by avoidance of accidents and casualties alone. However, railroads are exploring the potential for other benefits, which may include--

- Higher quality service, through continuous tracking of car movements.

- Reduced fuel consumption, through better pacing of trains (avoiding the need to take away momentum through braking and restore it through use of diesel power).

- More efficient use of existing physical plant, increasing effective capacity while avoiding further outlays to build additional tracks or sidings.

These potential benefits may be valued in the hundreds of millions of dollars annually. However, the extent to which these "business benefits" of PTC will be realized is a matter of continuing study and dispute within the railroad industry. Railroads such as Union Pacific and Burlington Northern obviously believe that the investment may prove worthwhile. Other railroads may determine that they can realize many of these same benefits using less expensive technology (e.g., cellular digital phones in lieu of data radio) or may not face the same capacity constraints that may motivate higher-density carriers.

Ultimately, privately owned freight railroads will make decisions regarding investment in PTC based on their own financial bottom lines. These decisions will powerfully affect the safety and cost of their operations.

Over time, the safety and affordability of publicly-funded intercity and commuter rail service will depend upon the freight railroad's commitment to PTC investments. If freight railroads deploy the communication infrastructure to support PTC and equip their locomotives with interoperable PTC, the incremental cost of this safety system for passenger carriers will be quite low. Extensive use of PTC by freight railroads will keep the cost of marginal line capacity lower, as well, benefitting passenger railroads and their customers.

Benefits of a nationwide surface LDS would not be limited to freight and passenger railroads. Precise positioning creates the potential for highway-side benefits, as well, including systems that could provide enhanced warning for collision avoidance at highway-rail crossings. As in the case of PTC, additional expenditures would be required to realize these benefits. Those expenditures would have to be justified based on their merits and after appropriate research and demonstration.

In sum, the costs of completing the LADGPS system are quite low in relation to the potential benefits that a completed system could facilitate. Because LADGPS will cost significantly less in pubic and private investment than the principal LDS alternative (transponders), its implementation could provide the critical impetus for PTC, if private business decisions are in doubt. Further, LADGPS offers the opportunity to provide a common positioning method for highway and rail, with the possibility for significant intermodal benefits.

6.0 Conclusions

Based on available information, USCG DGPS offers the greatest likelihood of meeting location determination requirements for PTC systems. Since low frequency/medium frequency beacons offer the best area coverage in the immediate future, a DGPS system such as the Coast Guard's LADGPS will provide the railroad infrastructure with a seamless navigation and positioning system in both urban and rural areas of the country. Other benefits of this architecture include the ease of system compatibility with highway and waterway systems under development or deployment. Intelligent Transportation Systems currently under consideration may include the USCG LADGPS system in their navigational and positioning system architecture.

Early, full deployment of USCG LADGPS as recommended in the DOT/NTIA report could provide a seamless and reliable location determination capability that can support and hasten the deployment of positive train control systems, while helping to achieve synergies between PTC and other Intelligent Transportation Systems. Public/private partnerships could hold down the incremental cost of deployment. Positioning services that are available to all users can serve as integrating element for all facets of a National Transportation System.

Maritime Differential Global Positioning System

CDR Doug Taggart

Radionavigation Division
USCG Headquarters (G-OPN)
2100 2nd Street S.W.
Washington DC 20593
202-267-0281 (fax - 4427)

Radionavigation Program

- International Agreement
  - SOLAS ... requires signatory nations to establish, maintain and provide information on aids to navigation.....
- Authority
  - 14 USC 81 ... the Coast Guard may establish, maintain and operate...
- Regulation
  - 33 CFR 66.01d ...electronic aids to navigation as private aids will not be authorized.

Maritime Navigation Requirements

- Accuracy, Integrity, Availability
- Phases of Navigation
  - Open Ocean
  - Coastal
  - Harbor and Harbor Approach
  - Inland

Federal Systems vs Requirements

Phase	Radio-beacons	Loran	Omega	GPS	DGPS
Ocean			□	□	
Coastal	□	□		□	□
HHA					□
Inland					□

Coast Guard DGPS

- Fielded to meet the Harbor and Harbor Approach Phase of Maritime Navigation
  - 8 to 20 Meter navigation accuracy
  - No Federally provided system existed before
- Initial work began in mid-1980's through CG R&D efforts
  - Design focused on high reliability/redundancy
  - System standardization as a key initiative
  - Commercial partnerships was critical to success

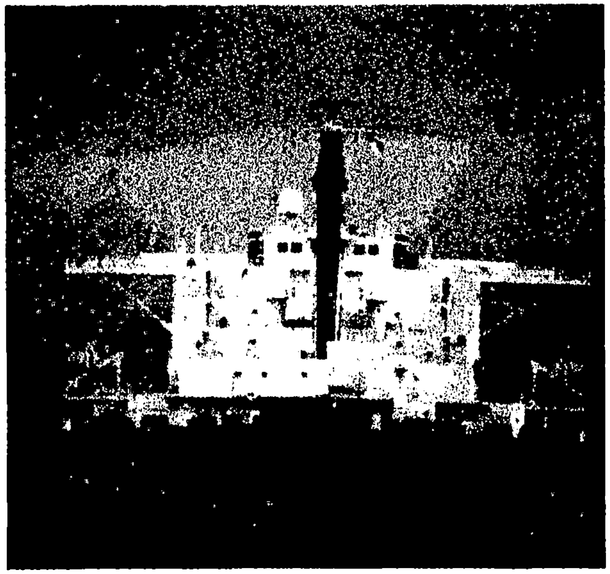
DGPS Resources

- $14.4 million expended to implement the current system
- $35 million spent from mid-1980's to date (includes all R&D)
- Annual O&M costs (includes 51 personnel) is $4.4 million

Coast Guard DGPS Services

- A success story in Government Agency Partnerships
  - U.S. Army Corps of Engineers
  - National Geodetic Survey
  - National Oceanic and Atmospheric Administration
- The Future holds more
  - Federal Railroads Administration
  - Tennessee Valley Authority
  - Others?

Coast Guard DGPS Benefits

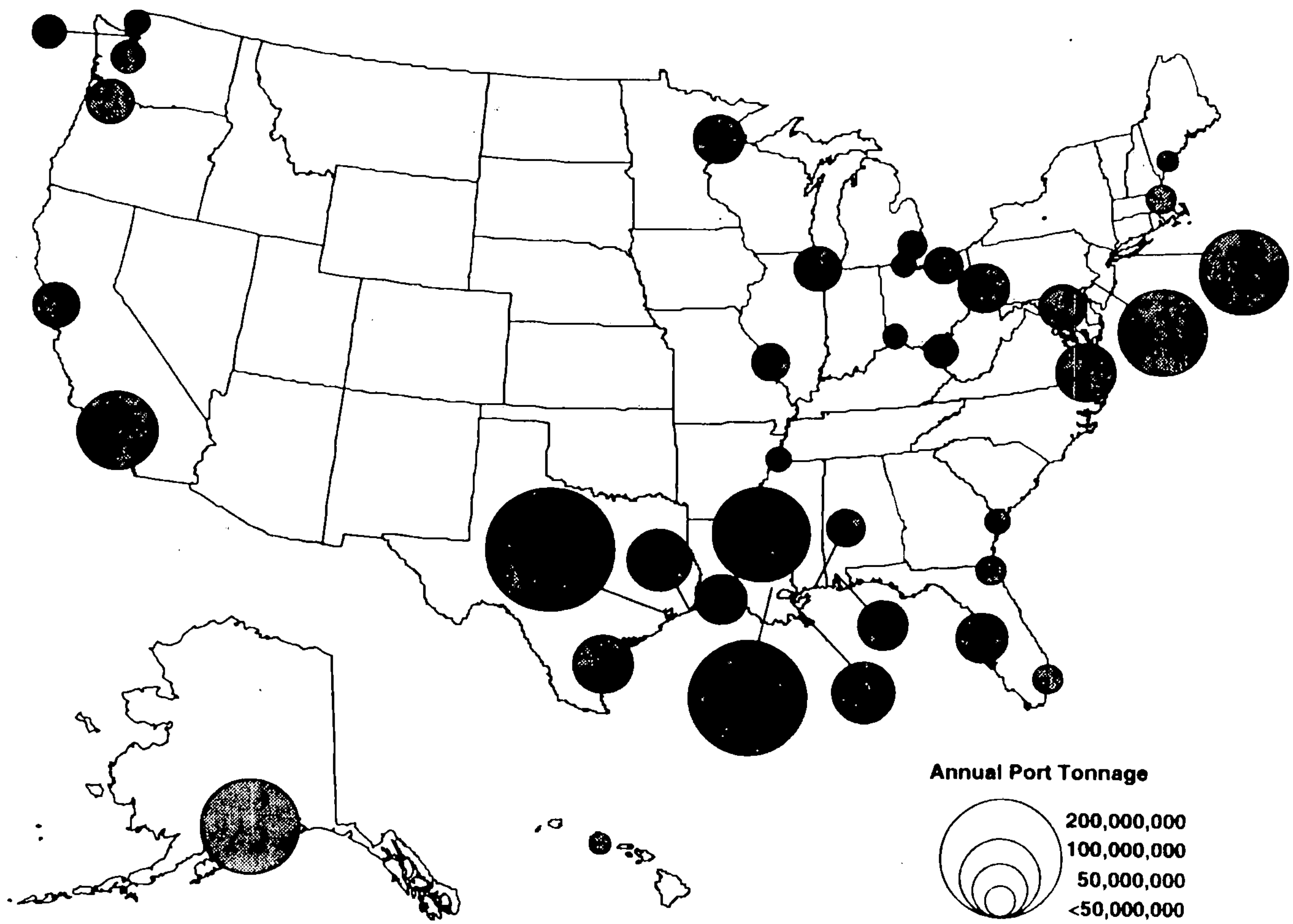


Vessel Traffic System

Buoy Positioning

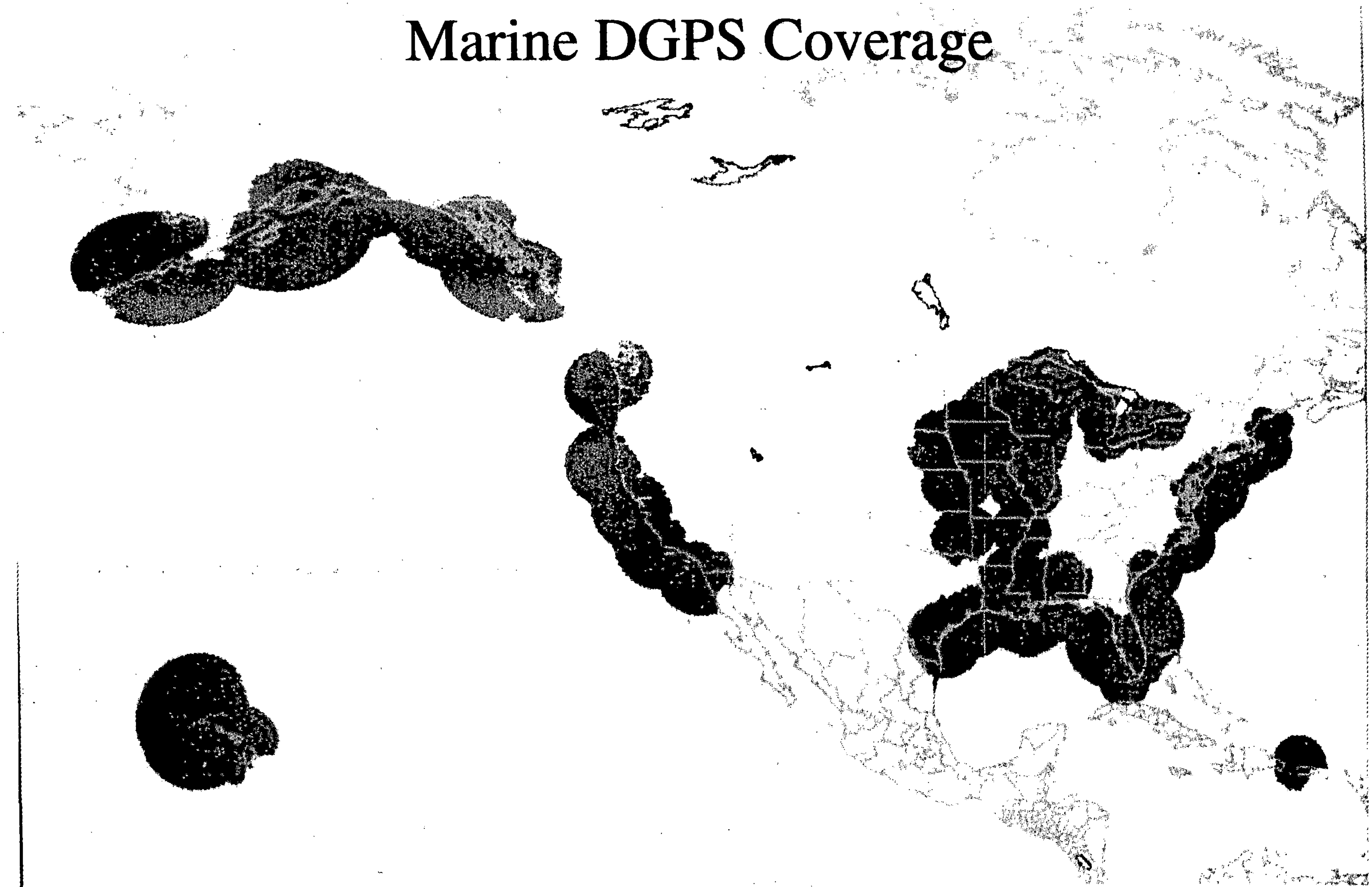
Ports with Total Tonnage Greater than 10 million tons: 1993

(source: Transportation Statistics Annual Report 1995)

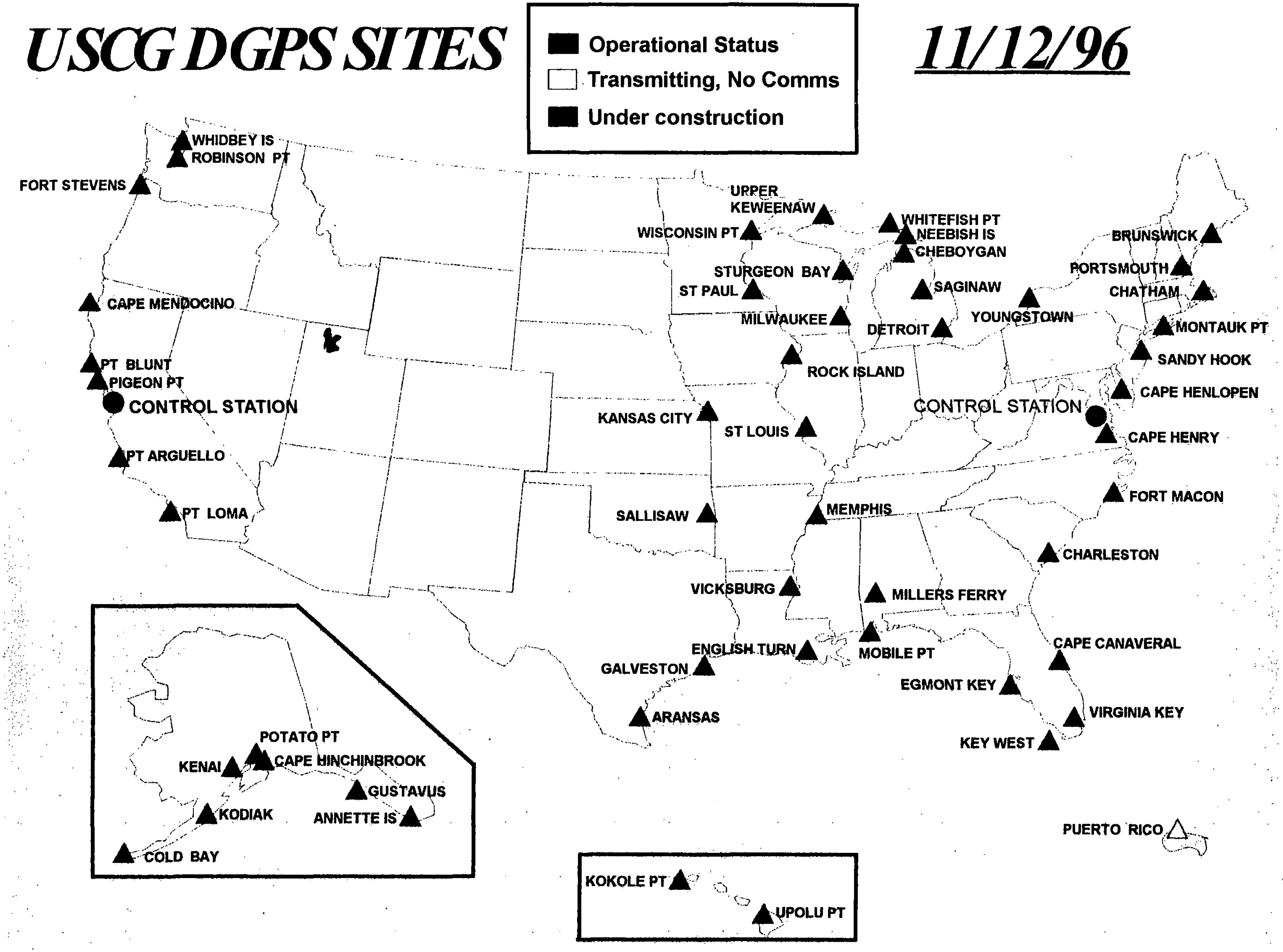


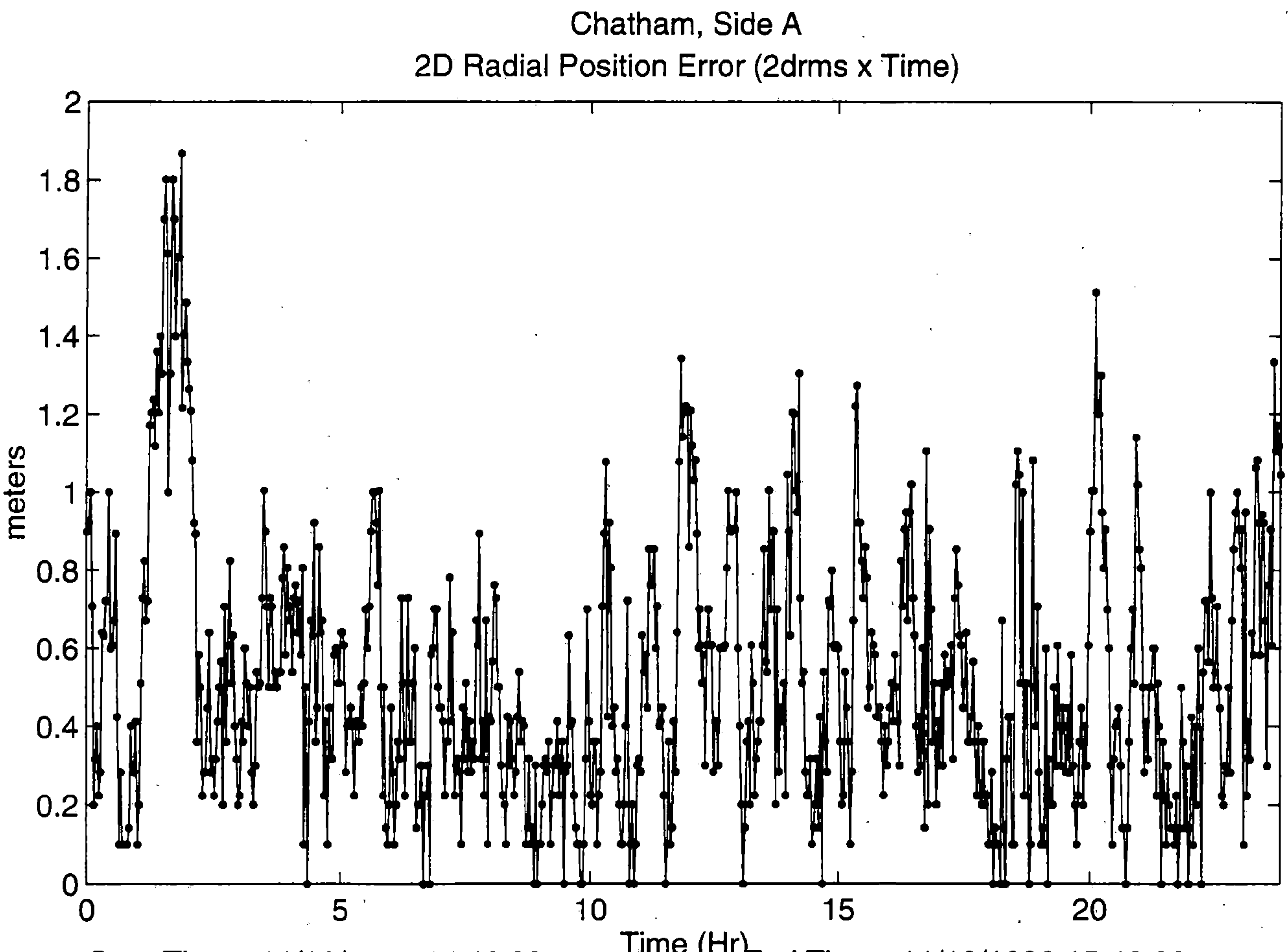
Note: Several ports have been combined (such as Los Angeles and Long Beach)

Marine DGPS Coverage

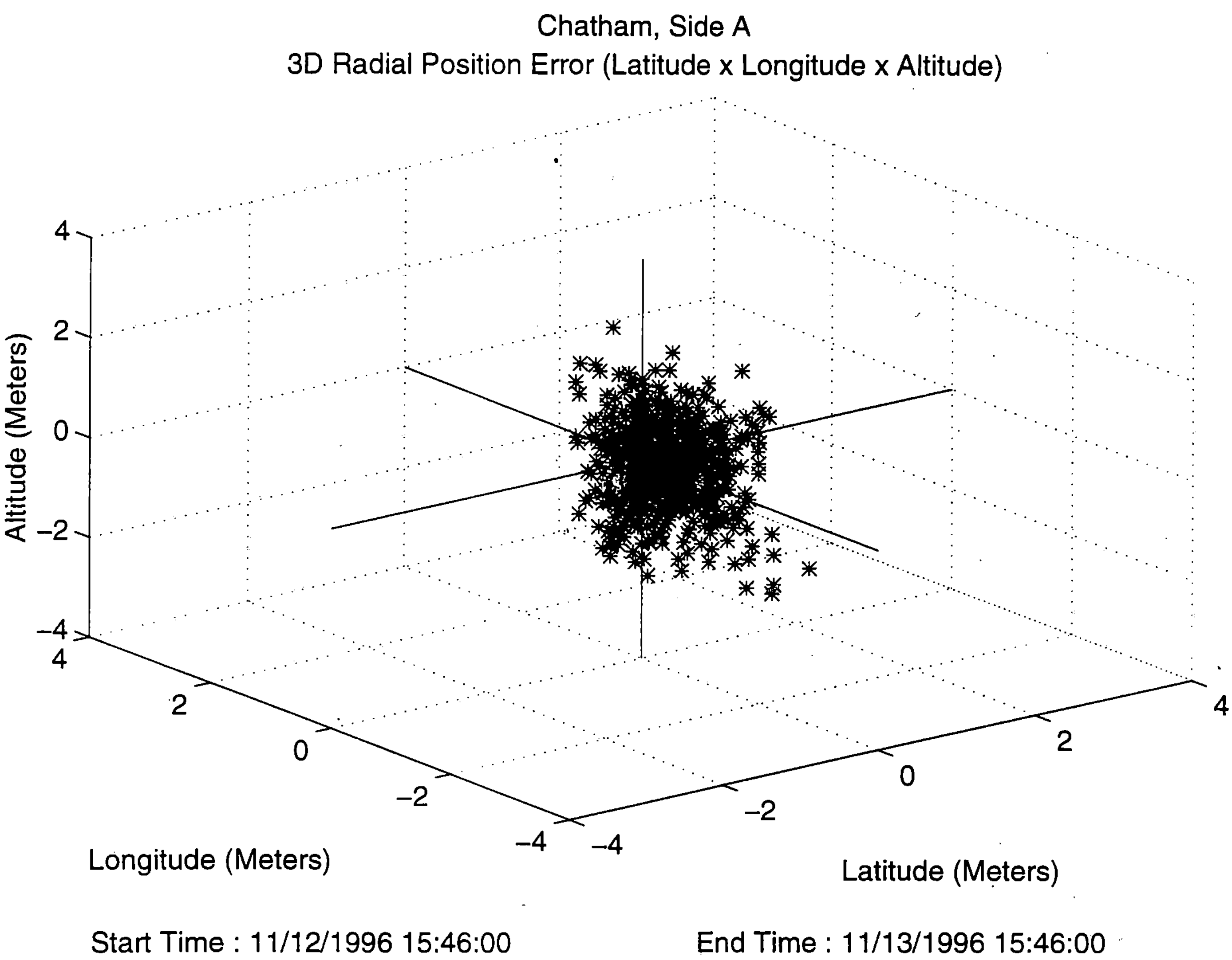


USCG DGPS SITES 11/12/96





Start Time : 11/12/1996 15:46:00			End Time : 11/13/1996 15:46:00			
# Points	=	715	Mean	=	0.5192	m
Minimum	=	0 m	Std. Dev.	=	0.3372	m
Maximum	=	1.868 m	95th Per.	=	1.2	m


Chatham, Side A
3D Radial Position Error (Latitude x Longitude x Altitude)
Altitude (Meters)
4
2
0
−2
−4
4
2
0
−2
−4
Longitude (Meters)
−4
−2
0
2
4
Latitude (Meters)
Start Time : 11/12/1996 15:46:00
End Time : 11/13/1996 15:46:00

Full Operational Capability

- CG DGPS Performance Specifications
  - Accuracy
    - (Better than 10 meters (2DRMS), .1 knots velocity determination)
  - Integrity
    - (Time to Alarm) 2 seconds @ 200bps
  - Coverage
    - CONUS coast navigation zone (20 to 50nmi)
  - Availability
    - 99.7% single site , 99.9% VTS areas (30 days)

USCG Navigation Information Service

Commanding Officer
USCG Navigation Center
7323 Telegraph Rd
Alexandria, VA 22315-3998

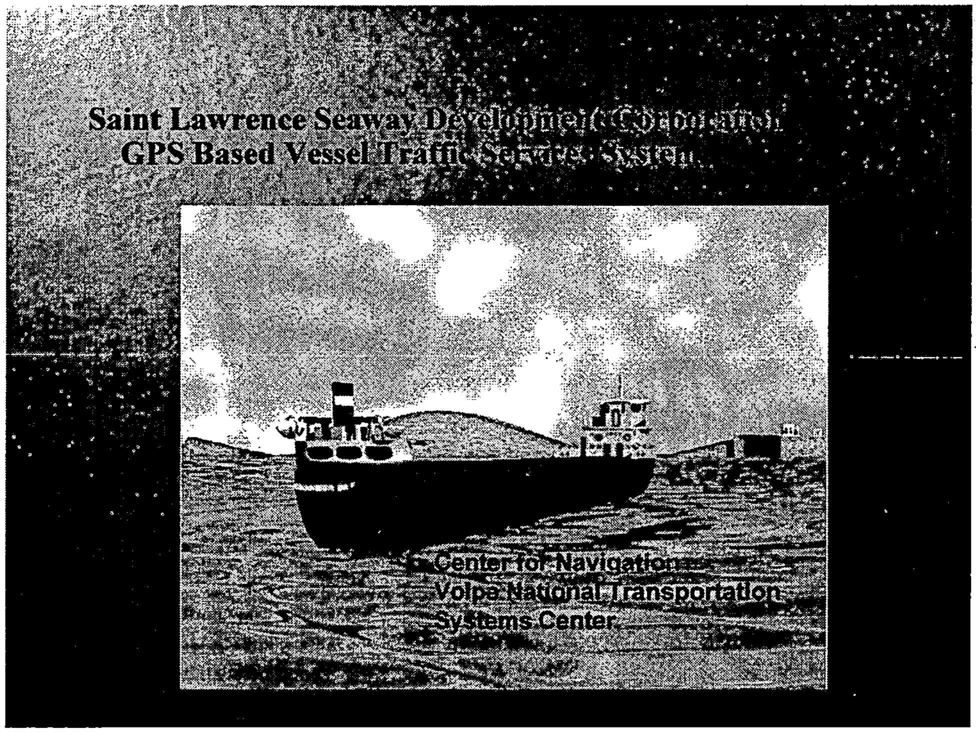
(703) 313-5900 (24 hours per day)
http://www.navcen.uscg.mil (Internet Home Page)

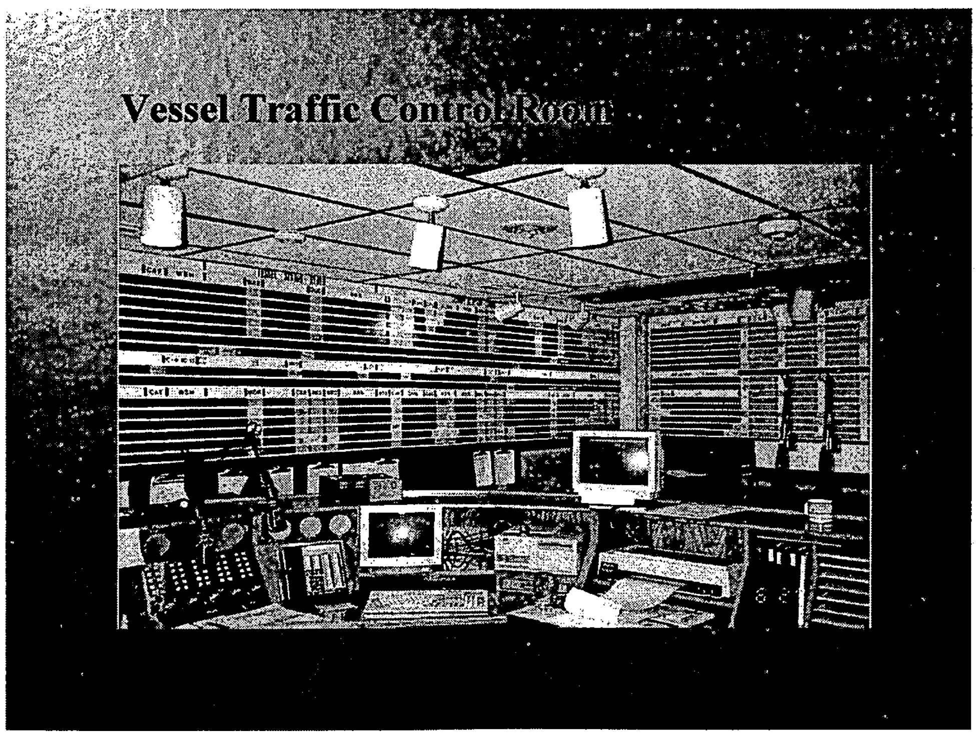
GPS Applications at the Saint Lawrence Seaway

Presented by:

GPS Applications

- GPS Based Vessel Traffic Services System
- DGPS Buoy Positioning System


Saint Lawrence Seaway
GPS Based Vessel Traffic
Center for Navigation
Volpe National Transportation
Systems Center


Vessel Traffic Control Room

Automated VTS System

Automatic position and speed monitoring contributes to:

- Accuracy
  - Position reports and [illegible]
- Efficiency
  - Schedul[illegible]
- Safet[illegible]
  - [illegible]
  - [illegible]

Requirements

- Coverage in U. S. Sectors
- Vessel Information
  - Vessel ID
  - Vessel latitude/longitude
  - Course over bottom
  - Speed over bottom
  - Time of position [illegible]
- [illegible]

System Elements

GPS

- GPS based VTS system augments existing ... SLSDC
- GPS Standard Positioning Service ... monitoring

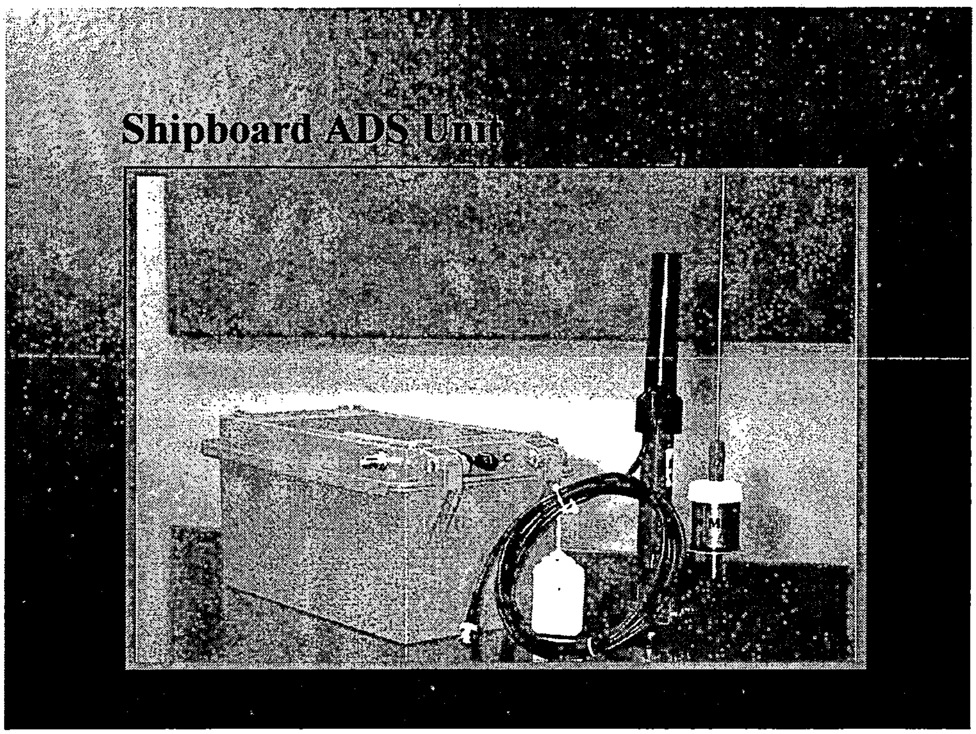
Shipboard equipment

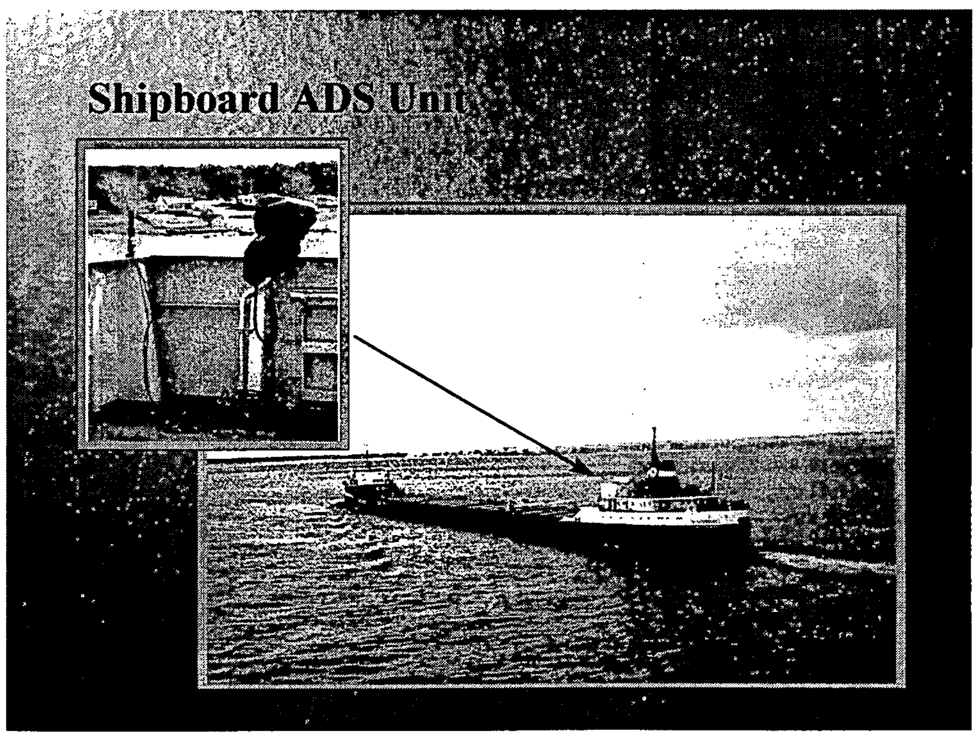
- An Automated ...

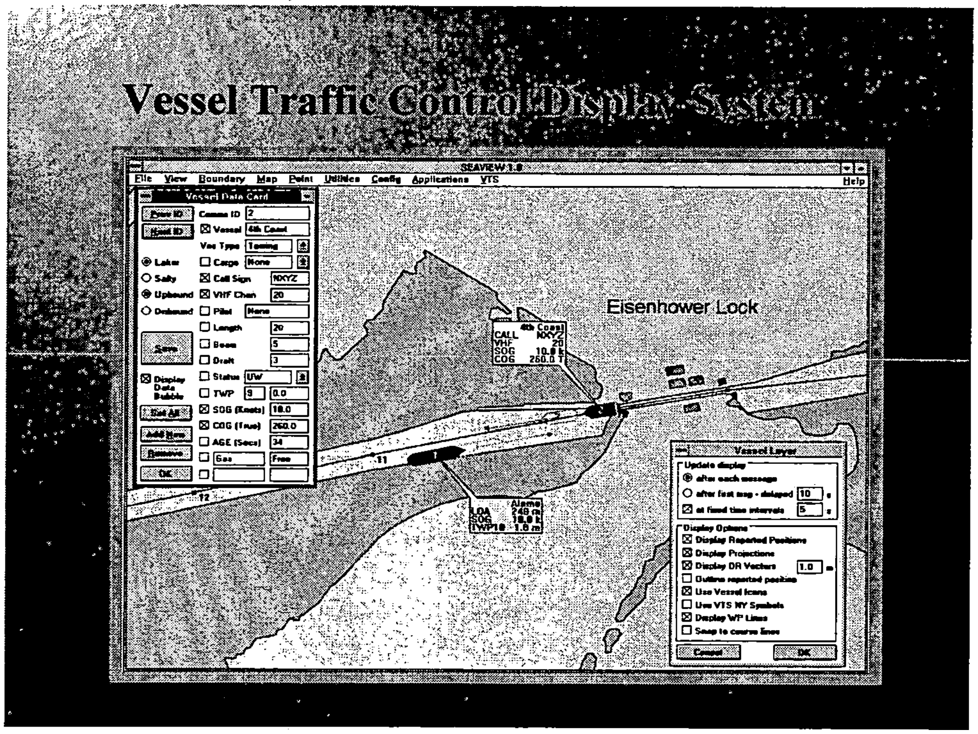
Communications

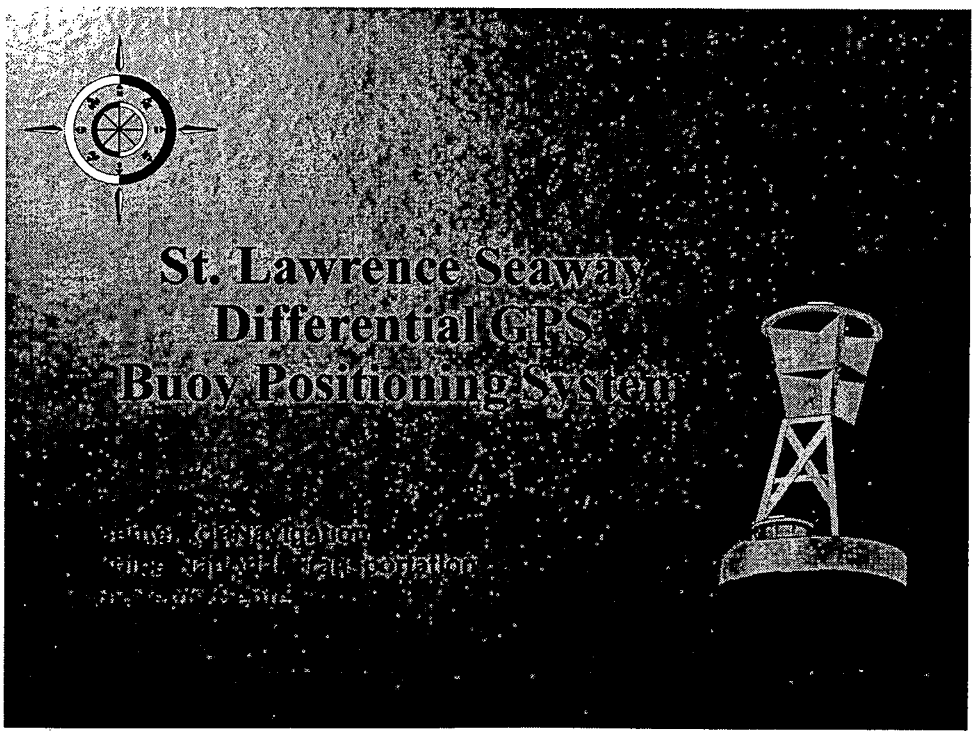
Shipboard ADS Features

- Low cost – less than $2,500
- Battery operation
- External DC voltage input: 10 to 35 volts
- Autonomous hands-off GPS operation
- Autotransmit at assigned time slot ... time
- Data transmitted:
  - Vessel ID
  - Latitude/longitude


Shipboard ADS Unit


Shipboard ADS Unit

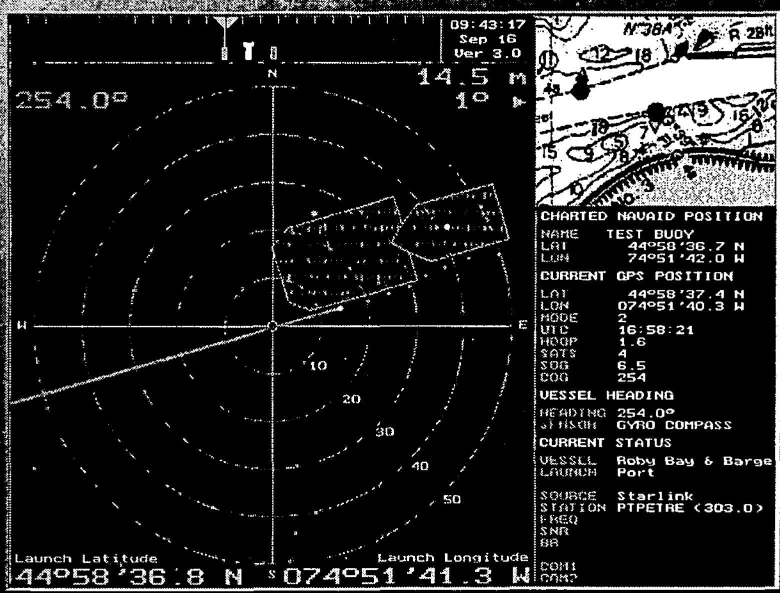

Vessel Traffic Control Display System
Vessel Data Card
Eisenhower Lock
Vessel Layer


St. Lawrence Seaway
Differential GPS
Buoy Positioning System

Program Goals

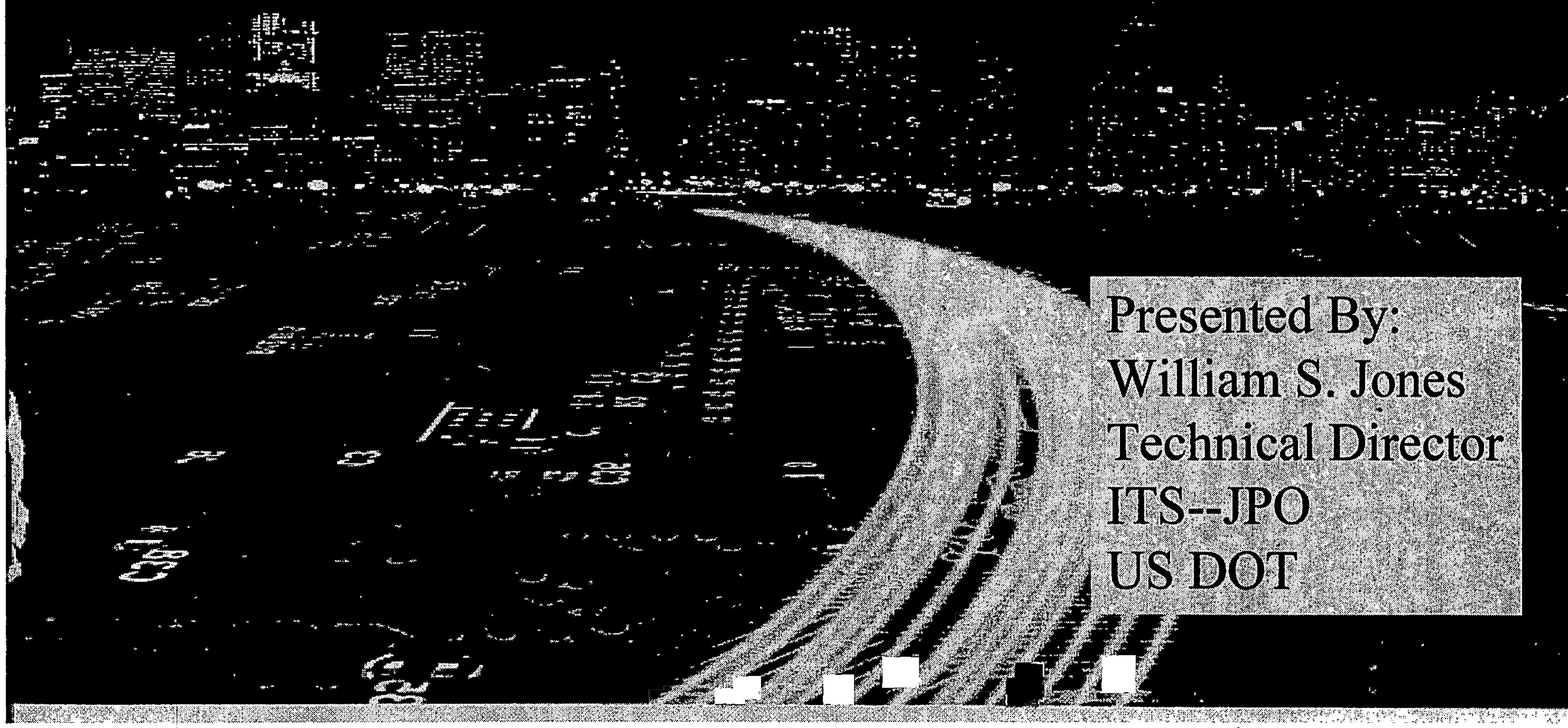
- DGPS Buoy Positioning System
  - Easy to use
  - Accurate and reliable
  - Reduce time and cost
  - All weather operation

DGPS Buoy Positioning System Display



GPS in Surface Transportation

November, 14 1996



Presented By:
William S. Jones
Technical Director
ITS--JPO
US DOT

Approximately 100,000 Commercial Vehicles Have GPS

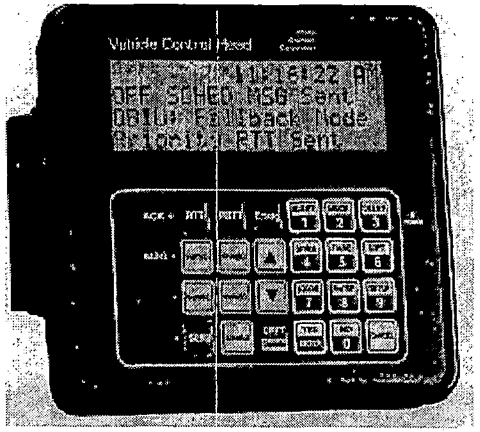
- Long Haul Trucks
- Local Delivery
- Taxis

<u>Provides</u>

- Match Truck to Load
- Reduces Out-of-Route and Dead Head Miles
- More Deliveries per Day

Over 15,000 Public Transit Buses Utilize GPS

- Improves Schedule Adherence -- 20%-30%
- Improves Fleet Utility -- 10%
- Provides Real Time Traveler Information
- Enhances Passenger and Driver Safety



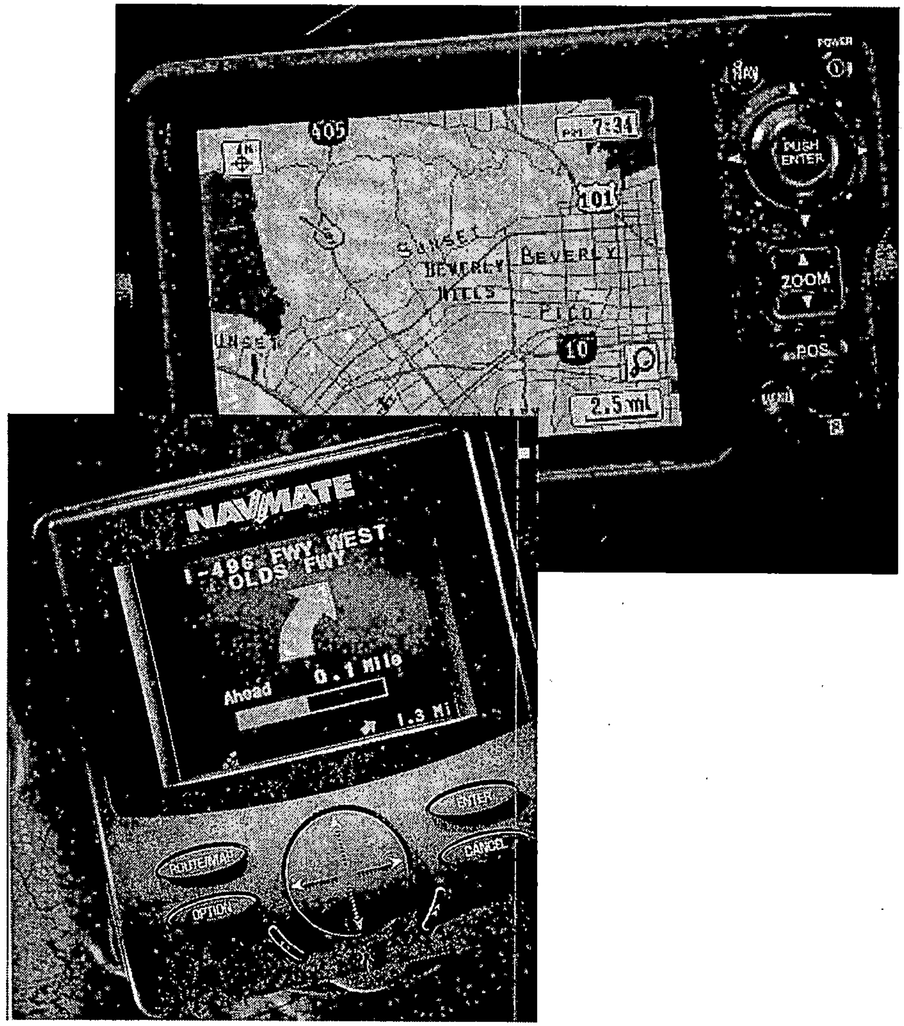
Numerous GPS Based Products Available for Private Autos

- MAYDAY
  - Available on
    - Cadillac
    - Lincoln
- Theft Protection

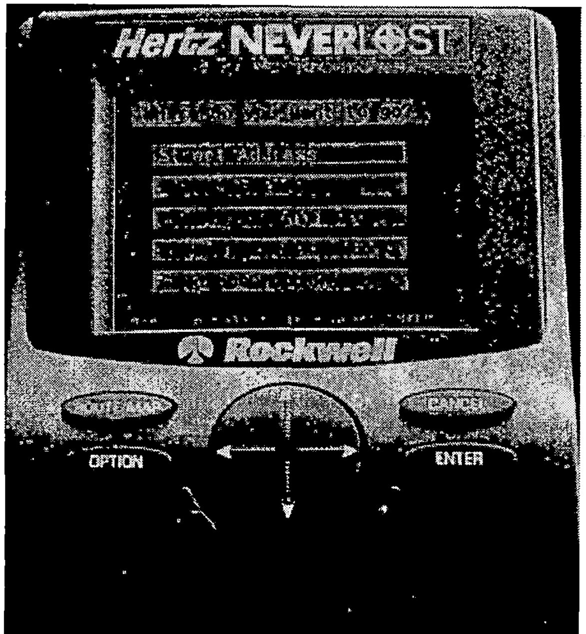
Route Guidance Will Become Standard Equipment

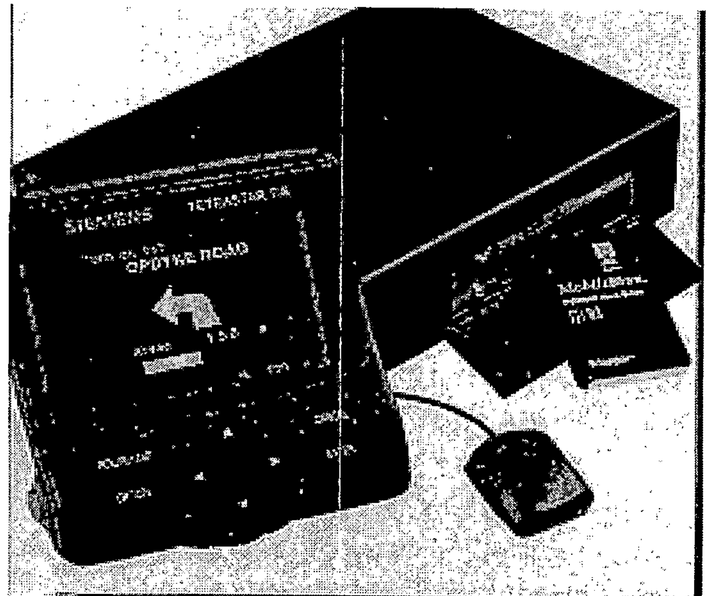
<u>**Provides**</u>

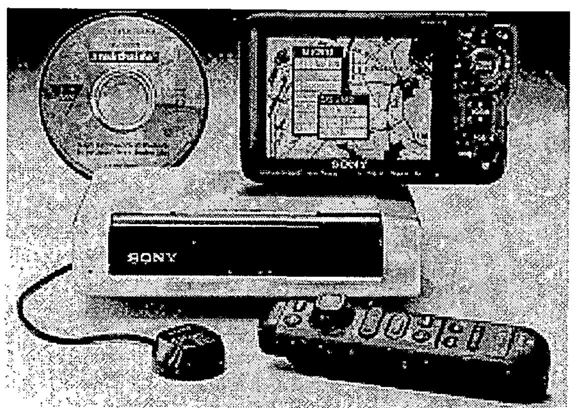
- Trip Planning
- Detailed Driving Directions
- Traffic Status
- Alternate Routes

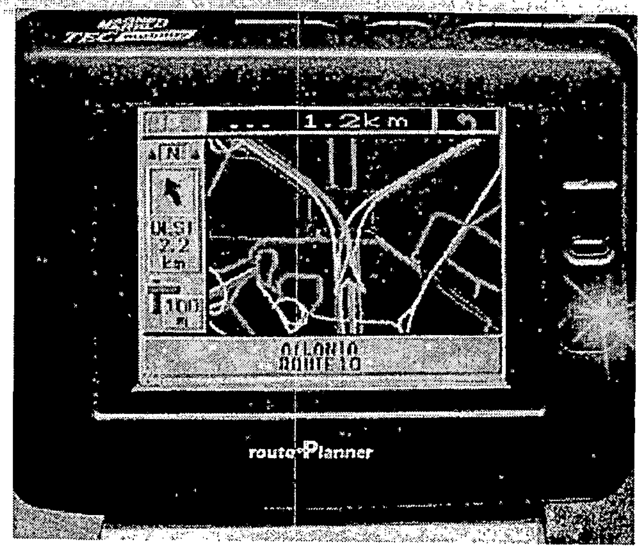


Products Abound









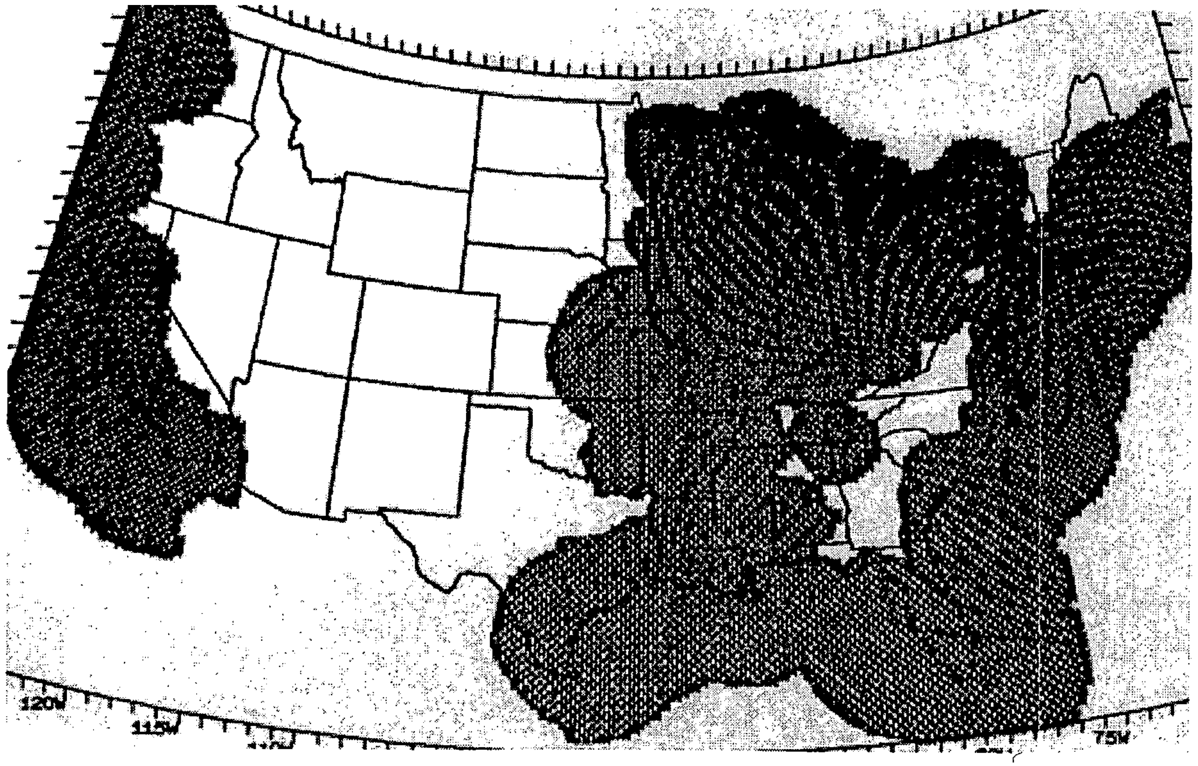
Next Step -- More Accuracy

Basic GPS Provides 100M Accuracy

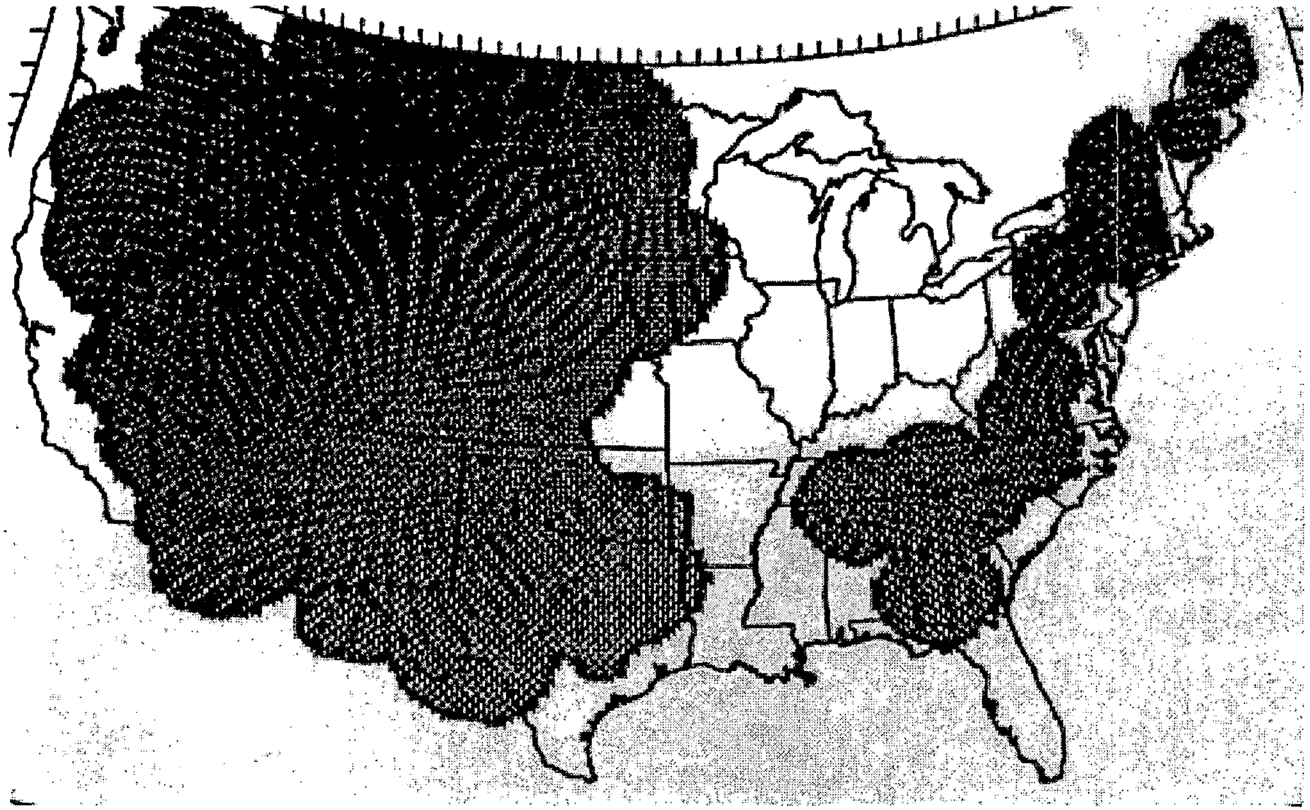
Differential Provides 5M Accuracy

- Coast Guard Has Differential GPS Operational
- Transmits in UHF

US Coast Guard Coverage



US DOT Planning to Complete Continental US Coverage



KINEMATIC GPS TECHNOLOGY
AND
POTENTIAL APPLICATIONS

Federal Railroad Administration
Office of Research and Development
Technical Symposium
Washington, DC
November 14, 1996

Wang Tang and James L. Maida
ARINC
4055 Hancock Street
San Diego, CA 92110

KINEMATIC GPS TECHNOLOGY AND POTENTIAL APPLICATIONS

Wang Tang and James L. Maida
ARINC
4055 Hancock Street
San Diego, CA 92110

INTRODUCTION

On July 17, 1995, the U.S. Air Force announced that the GPS satellite constellation had met all requirements for full operational capability (FOC)[1], that is, the system met all of the requirements specified in various formal performance documents, and users could use the system with complete confidence in its performance. This declaration marked the beginning of a new era in the application and use of positioning technologies, forever changing the way people and things move from one place to another.

There are two basic modes of operation for the GPS users; Standard Position Service (SPS), and Precise Positioning Service (PPS). One of the major differences between these two modes is the end user accuracy, with PPS accuracy being roughly an order of magnitude better than SPS. Since PPS is reserved for the military, the commercial users are limited to the SPS mode of operation and its associated accuracy. But, because of certain enhancement techniques known as Differential GPS (DGPS) and Kinematic GPS (KGPS), the users have access to additional operational modes that provide accuracy that are increased significantly.

Implementation of DGPS and KGPS modes of operation can involve land, aviation and maritime applications. Since many papers have been written on the various uses of DGPS, the primary objective of this paper is to concentrate on the KGPS operational mode. This paper will introduce the principal of KGPS, provide examples of expected accuracy, and discuss a few applications of the technology. Uses include the potential implementations for providing assistance to aircraft for precision approach, vessels for precise positioning and docking, and for enhancing railroad maintenance operations.

GPS PERFORMANCE OVERVIEW

Depending on the user's design and implementation, the basic GPS signal has the potential to provide commercial users positioning accuracy ranging from 500 meters, with Standard Positioning Service (SPS), to a few centimeters when enhanced by carrier phase tracking and processing. GPS SPS is the system performance available to commercial users — those who do not use the Precise Positioning Service (PPS) signal, which is reserved primarily for military applications. The GPS SPS signal specification[2] stipulates that the following positioning accuracy be provided to uses on a worldwide basis:

⇒ 100 m horizontal error 95% of time
⇒ 156 m vertical error 95% of time
⇒ 300 m horizontal error 99.99% of time
⇒ 500 m vertical error 99.99% of time

Although the SPS level of accuracy is sufficient for many users, it is not adequate for certain applications, such as distinguishing which track among many parallel tracks a train is located on. A more accurate system can be achieved by a technique call differential GPS (DGPS).

In the differential mode, a GPS ground reference receiver (station) is installed at a precisely surveyed location. The ground reference station can accurately estimate dominate GPS errors, such as Selective Availability (SA), ionospheric and tropospheric delays, satellite ephemeris error, and clock bias. Other remote receivers in the vicinity of the GPS reference station can then use the estimated GPS errors in real-time, broadcast via data link transmission, to offset their GPS measurements. This results in much better positioning accuracy, typically on the order of 1 to 5 m, depending on the rate of corrections generated by the reference station and the distance between the reference station and the user. The distance, often expressed in miles or kilometers, influences the remote user's accuracy as a result of spatial decorrelation. Spatial decorrelation, the primary source of DGPS error, is caused by the differences in atmospheric effects observed at two different sites (i.e., reference station and user). In general, the greater the distance between the sites, the greater the error. A conservative rule of thumb is 1 cm error per 1 km separation[3] A sub-set of the DGPS mode, where the reference receiver is allowed to move "relative" to a moving user, although slightly less accurate, is known as "relative GPS."

More recently, a new technique, called Kinematic GPS (KGPS), has become a major focus of many researchers in the GPS community. The KGPS mode has the potential to achieve one or two orders of magnitude better than DGPS. In addition to position and velocity information, KGPS can also provide attitude and attitude rate information, if needed. KGPS operates in a similar manner to DGPS, whereas a reference receiver computes errors in the GPS satellite signal and provides localized corrections to end users. Similar to DGPS, the KGPS implementation also allows an operational mode whereas the reference receiver is not required to remain fixed. Since the kinematic corrections are based on computing the differences between two or more receivers, the reference receiver and user receiver(s) can each posses movement.

If both receivers are stationary, albeit for only a few minutes, this is known as "surveying." When one receivers is moving relative to a fixed receiver, this is known as "tracking." But, if each receiver is collocated on the same platform, either stationary or moving simultaneously, the platform's attitude information can also be computed precisely and is known as "attitude determination." Depending upon whether two or three receivers are collocated-located will determine if only two, or all three attitudes, can be derived. Any of these capabilities can be implemented either in a "post processing" (non-real-time) or a "real time" configuration, if a data link is present.

PRINCIPLE OF KGPS OPERATION

Typically, a GPS receiver design includes a phase-lock-loop (PLL) to track the signal and be able to measure the phase angle of the carrier. However, when GPS was conceived more than twenty years ago, the carrier phase measurement was not considered to be a direct observable. Therefore, it was only used to generate delta-range measurements used for velocity computation, derived by differencing two consecutive carrier phase measurements. Subsequently, the ultimate benefits of using carrier phase measurements were largely ignored by most military and commercial receiver manufacturers. Although it is available internally, not many receivers treat it as a viable, useful measurement. Only recently have receivers begun implementing carrier phase tracking and reporting capability. As they become more readily available, they are becoming relatively affordable.

With two receivers operating simultaneously, the GPS carrier phase measurements can be used to determine the baseline vector from one antenna phase center to another regardless of whether they are stationary or moving. As shown in Figure 1, between two receivers tracking the same satellite, the carrier phase difference of a particular satellite is the dot-product of the line-of-sight unit vector from the receivers to the satellite and the baseline vector. With phase measurements from four or more satellites, it is possible to precisely determine the baseline vector in an earth-fixed coordinate frame. The term kinematic refers to the fact that this baseline vector computation is instantaneous and no information regarding dynamics of antennas is required. Since the carrier phase can be measured to within a few degrees of a whole wavelength, which is 19 cm, by processing carrier phase the potential positioning accuracy is on the order of millimeters, when two antennas are separated by less than 10 km. As the separation increases, the accuracy degrades due to the spatial decorrelation effect, although to a lesser degree than in the DGPS mode. The current KGPS achievable accuracy, as a function of baseline length, is as follows:

Accuracy	Baseline Length
2 cm	0 to 10 km
12 cm	10 km to 15 km
36 cm	15 km to 35 km
1 m	35 km to 250 km

To apply the KGPS technology to the survey world, one receiver/antenna is typically placed at a fixed and known location, while the other is placed at a location that is being "surveyed." If one receiver/antenna remains at a surveyed location and the other is moving, then a baseline vector can be used to determine and "track" the precise location of the moving receiver/antenna. When both receivers/antennas are installed on a moving platform, the resulting baseline vector can be used to determine azimuth and elevation. If three or more receivers/antennas are installed on the same moving platform, a third dimension of attitude (i.e., roll or tilt) can also be determined. In fact, three-dimensional GPS-based attitude information could potentially be more accurate and more cost-effective than other existing attitude sensors, such as a gyro and magnetic compass.

To demonstrate the positioning accuracy of kinematic GPS in the "tracking" mode, a ground test was recently conducted on Fiesta Island, located in San Diego, California. Fiesta Island's size is approximately 3 km north-south by 2 km east-west, with an encircled kidney-shaped, one-way road, positioned nearly parallel to the shoreline. During the test, a reference station was established on the roof of ARINC's San Diego office, which is located 2 km south of the island. A roving receiver/antenna was installed in a car outfitted with the KGPS mobile system and some recording equipment. At the start of the tests, initially the car's removable antenna was placed on a surveyed benchmark, located a few feet off the road and two feet above ground. The antenna was then returned and placed on top of the car, which was then driven for 10 complete circuits around the island. At an average speed of 30 miles per hour, the total test duration was approximately 70 minutes. To complete the tests, the antenna was once again placed on the same benchmark. This was performed in order to have loop closure, which validates the data integrity.

Figure 2 presents the complete horizontal trajectory for the entire 10 circuit test duration. Because of the scaling, it is not possible to distinguish the system measurement error of the actual variation between each of the ten repeated tracks, resulting in 10 overlapping tracks appearing like a single track. Since the surface of road is relatively flat, the vertical profile for each of the ten circuits, should be quite similar. A vertical profile of position versus time is shown in Figure 3, and illustrates this point. It shows that the altitude change was very small for each circuit, but more importantly that each circuit was identical. To better highlight the potential accuracy of KGPS, Figure 4 illustrates the vertical trajectory as seen from a side view angle (i.e., vertical position verse north position) for the each of the ten circuits. It is observable that the individual tracks are within 10 centimeters vertically of each other. Although the horizontal accuracy is even better, it can not be observed because of the scaling limitations.

To demonstrate the achievable accuracy of attitude determination, a laboratory test was conducted using two receivers with their antennas separated by 2 meters. Although it is a stationary test, the results should not change at all in a dynamic environment provided that carrier phase measurements from both receivers are available. The data were collected over a 24 hour period, at rate of 1 Hz. At each second, an independent azimuth and elevation measurement was computed. Although the absolute truth of azimuth was not known, the statistics of both the mean and standard deviation indicate that the mean value should be equivalent to the true azimuth, and the standard deviation provides a measure of accuracy. With more than 80,000 data points, standard deviations for azimuth and elevation were 0.124 and 0.257 degrees respectively

Attitude determination is a function of both phase-measurement error (noise) and phase center variation or offset (bias), and is the RSS of these two error sources divided by the baseline length. Phase noise is a function of the receiver, and is statistically relatively constant for a given receiver, while the phase center variation is specifically caused by the antenna. High performance receivers will exhibit lower phase noise, on the order of 1 mm, whereas poorer performing receivers will be in the order of 5 mm. For comparison, if phase noise is 3 mm and the antenna separation is one meter, it represents an attitude error of roughly 0.2 degrees. Since phase noise is a function of the quality of the receiver, a noisier receiver can obtain the same attitude accuracy as a less noisy receiver by increasing the baseline separation. Although they cost more, an advantage of higher performing receivers is that shorter baselines can be utilized. So, when shorter baselines are used the antenna phase offset may become a dominating error source. For example, if phase offset from an antenna is 1 cm, then this contributes approximately 0.5 degrees to the total attitude error.

DATA RATE CONSIDERATIONS

KGPS operation has essentially two major aspects, position and attitude determination.

For determining precise positioning (including "tracking"), a KGPS reference station is required that outputs kinematic carrier-phase "corrections." Position determination also requires that the phase measurement differences between the reference and user receivers be computed, so there is need to transfer the phase measurement between the two receivers. Although this can be implemented in either a "post-processing" or "real-time" configuration, the later requires use of a data link to up-link the corrections. But, when two or more receivers are being used to compute attitude only, since the baseline vector(s) are usually on the order of a few meters, the carrier phase can be measured directly by the user receivers and there is no need for up-linked "corrections" and a separate reference receiver. Therefore, attitude determination can always be computed in "real-time," so an associated data link is not required.

A question that is invariably asked is what is the minimum baud rate required for the data link. Unfortunately, there is no set answer. Currently, 9600 baud rate has served universal real-time-kinematic (RTK) well for navigation (i.e., no tracking) purposes.[5] It can be considered as a upper limit of using Kinematic GPS for navigation output only. But, slower rates may work equally well under certain circumstances. If you plot baud rate (x-axis) as a function of cost (y-axis), it has a cost curve that is flat for a large portion of the low-to-medium baud rates (the infrastructure costs are somewhat fixed for a given RF technology), until it reaches a point where it becomes very cost sensitive. At that point, at very high data rates it has a steep rise in costs associated with only an incremental increases in baud rate. If you look at a similar baud rate (x-axis) versus accuracy (y-axis) curve, you see a drastic change in accuracy as you move up the baud rate axis, until it asymptotically reaches a maximum accuracy that can not be exceed if the data rates were increased. Therefore, data rate in of itself should not be dictated as a design requirement. Rather, accuracy must be weighed versus affordability and other performance parameters, and should be decided as part of design tradeoffs when the overall system architecture is being developed. For a given accuracy level, one may have to sacrifice data availability or update rate, if data link implementation costs are an issue.

The real problem regarding the data rate requirements begins when one wants to perform position tracking. Depending upon whether it is one-way tracking (all users report position back to central station) or two-way tracking (central station in turn re-broadcast position information to the users), the demands on the data link can impact the data link requirements significantly. There are a number of additional factors, other that data rate, that can affect the position accuracy, namely:

- Initialization scheme
- Data latency
- Required position output rate
- Platform dynamics
- Other navigation aiding (if available)

For railroad applications, if the data rate from one place to another is a limiting factor, a number of measures can be used to overcome this restriction. A simple method is to compute KGPS position sparsely to lessen the data link requirement and use the known vehicle dynamics to extrapolate in between. This method will work well when minimum acceleration is observed. Another method is to take advantage of the information of surveyed tracks. By assuming that the train is always on these tracks and no where else, it is possible to smooth the trajectory with minimum support from the reference station.

KGPS APPLICATIONS

There are many applications which can benefit from the precise position and attitude accuracy available from KGPS, both in post-processed and real-time implementations. The earliest, and the one that has been around the longest, is surveying. Because this technology is now coming of age there are many applications that have yet to be thought of. As this technology takes hold and can be demonstrated many users will embrace the plethora of applications, all designed to make their job's easier, faster, cheaper or safer.

Applications are now beginning to surface that will impact the lives of users in all walks of life, not only on land but in the aviation and maritime communities as well. For the aviation industry, the application of KGPS will enhance overall navigation accuracy to assist in aiding existing navigation aides in improving their positioning and attitude determination capabilities. The precision information available from KGPS will contribute to allowing aircraft to land safely in little or zero visibility and to taxi safely to and from the gate and runways in adverse weather conditions. Land uses are seeing KGPS data to support precision farming, including controlled crop-dusting, to improve overall crop yields. For maritime applications, precise positioning and attitude information is being integrated with coastal, harbor and inland waterway electronic maps. This capability will provide the ship's operators or local pilots with enhance visibility and awareness, of all types of vessels and ship movements within the surrounding waters.

In recent years, GPS technology has been gaining acceptance within the railroad industry, although on a somewhat limited basis. For example, several railroads are evaluating the use of DGPS, integrated with other technologies, to assist in the implementation of future train control systems, currently referred to as positive train control. Some even suggest that DGPS can be used for performing railroad surveys[6] Although this is feasible, it may have limited use in helping to collect and store information on track location and attributes (i.e., average elevation), assets/facilities collection, and as input to track usage planning and wear models. This can be accomplished by mounting DGPS equipment on high-rail vehicles which stop at mileposts, signals, bridges and grade crossings, etc., to survey and store in a data-base for later recall. It was also suggested that DGPS could be used to support other railroad operations, such as maintenance, but would require repeated measurements and comparison with existing laser alignment systems. However, to take full advantage of the higher accuracy needed for supporting track survey and measurement, especially in real-time, KGPS may be more effective.

The precision positioning and attitude accuracy of KGPS can be used for the operation of track geometry cars, rail flaw detection vehicles, rail profile analysis vehicles, and curve analysis vehicles. Implementation of GPS technology for these applications require the centimeter survey capability only available from KGPS. Similar, but much less costly, a KGPS system can be implemented in much the same way as the Delta leveling system and AutoGraphliner lining systems that are used in the railroad industry today. In recent years enhancements have been made to lining systems, especially in use for high-speed tangent track, by integration of laser systems with the AutoGraphliner. Although this has added accuracy to the measurement, it also has added significant cost.

Use of three KGPS receivers could be implemented to replace the complex and expensive systems just mentioned. Such a KGPS System would establish the identical 'horizontal reference plane" of the Delta System, to allow accurate measurement of proper grade and super-elevation, as well as allowing precise alignment of track for determining curvature. In addition, it could be used to measure track smoothness, identifying the high and low points within sections of track, or interfaced with Grinding Machines to support individual rails resurfacing operations. A KGPS capability can also be integrated into the Jacking/Tamping Systems (JTS) or Surfacing Machines used today. Also, because it is relatively inexpensive, it can be installed in high-rail vehicles as well.

Integration with a JTS car or Surfacing Machine would help reduce overall operations and maintenance costs of the track maintenance equipment. First, it can eliminate the costly and complex measuring systems currently used. Secondly, since the high-rail vehicle would be much more accurate than today, and have the same accuracy as the JTS car, it would allow the high-rail vehicle to be used more frequently, to increase the number of accurate measurements for better monitoring of track conditions and trends. This would minimize the number of times the JTS car would have to be used, once again reducing the overall maintenance costs. Lastly, when used in conjunction with the JTS car, the high-rail vehicle can be used to traverse the section of track being maintained and can perform the measurements themselves, and much more quickly. The measurements can then be transferred to the JTS car via data link, eliminating the need for having the JTS car traverse the same section of track before returning to make the required track adjustments. This not only reduces the usage of the JTS car and crew, it assures maximum utilization of on-track time, and minimizes JTS equipment maintenance, as well as maintenance and operations labor costs.

SUMMARY

The introduction of GPS has brought about significant change to many people throughout the world. The advent of Differential GPS (DGPS) technology has meant even more change and has introduced new applications for the technology. Following in it's footsteps, Kinematic GPS (KGPS) technology is about to revolutionize how we do business in the future. As this technology matures and the cost of the equipment continues to decline, we will see many more uses. It will find it's way into new land, aviation and maritime applications, many of which have not even been thought of today.

Of the GPS technologies, KGPS holds the greatest opportunities and challenges. From use in surveying and precision farming, to precision landing and taxiing aids for aircraft, and precision maneuvering and docking of large vessels and ships. One of the more intriguing applications involves usage within the railroad industry, specifically for track maintenance operations. The centimeter accuracy of KGPS further translates to highly accurate positioning and attitude information which can be used effectively in allowing the rail industry to accurately measure, monitor and maintain track. Currently, the rail industry uses complex and costly measuring equipment, which are both costly to procure and maintain. A less expensive, reliable and low maintenance KGPS Rail Condition and Measurement System could be developed which would eliminate the potential need for such systems. Utilization of KGPS technology in track maintenance operations could help provide track conditions that ensure a quality and safe ride.

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[4] *The NovAtel RT-2 Positioning System*, NovAtel, Calgary, Canada, 1996.

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[6] Spradley, L. H., et al. "Dynamic GPS for Railroad Surveys: A Case History, " *ION National Technical Meeting*, January 91

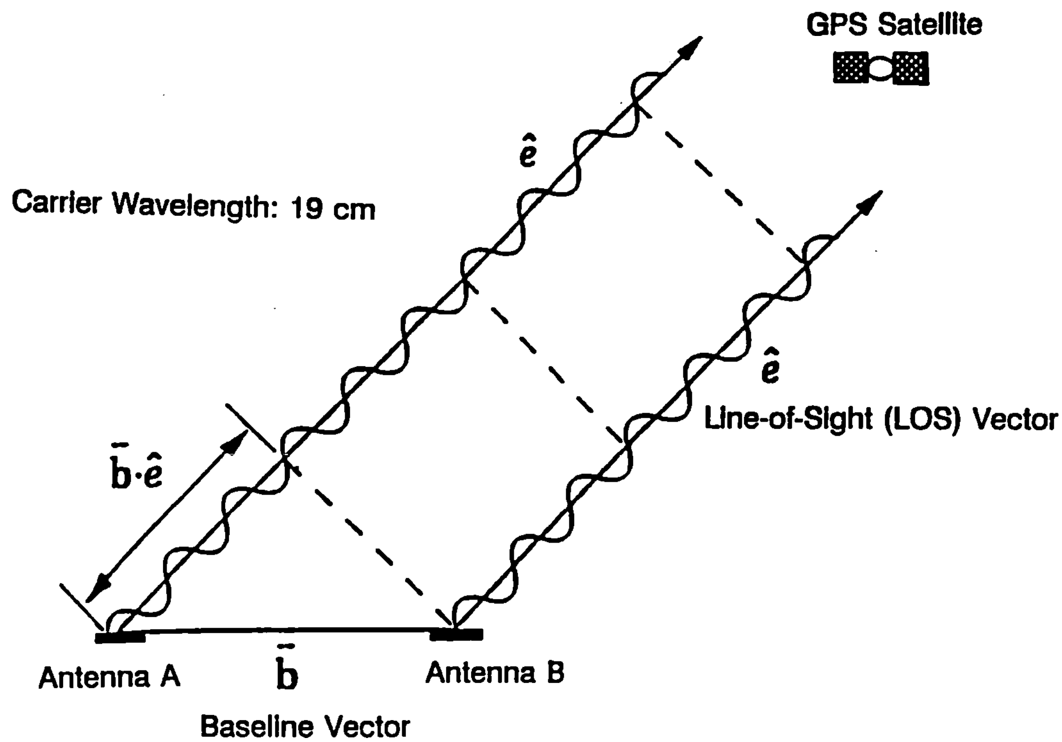

Figure-1 Carrier Phase Tracking

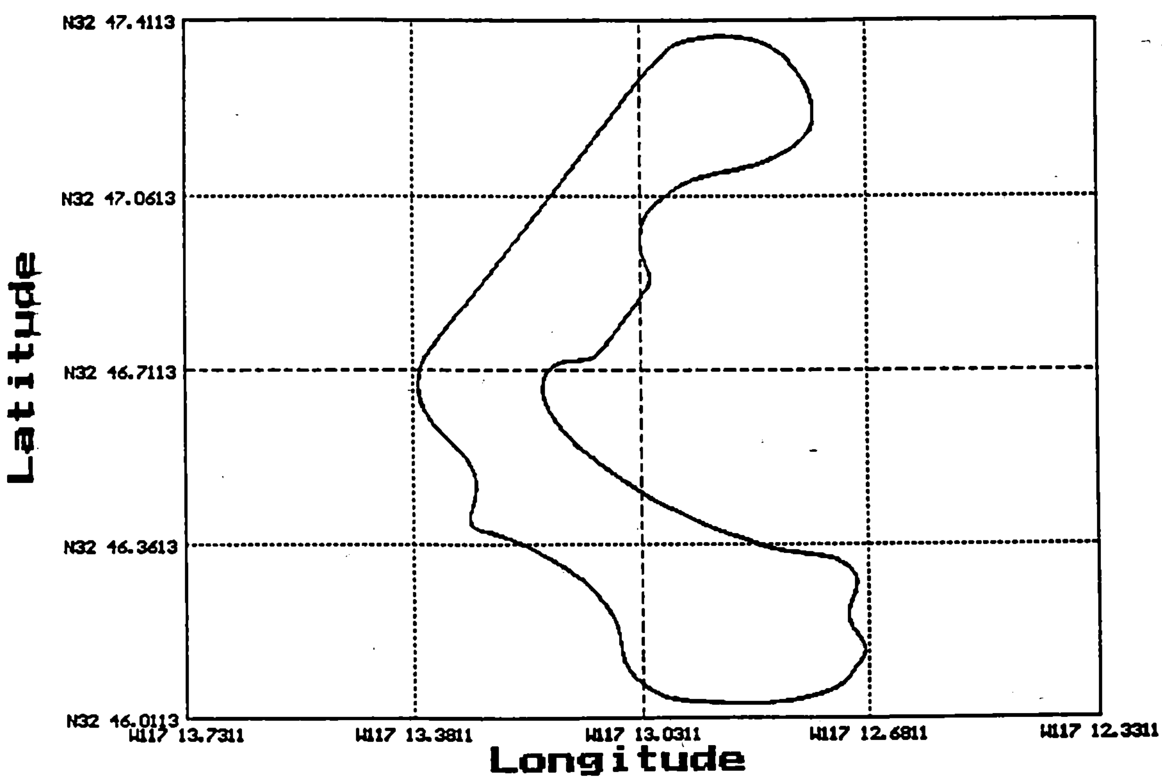

Figure-2 Horizontal Trajectory

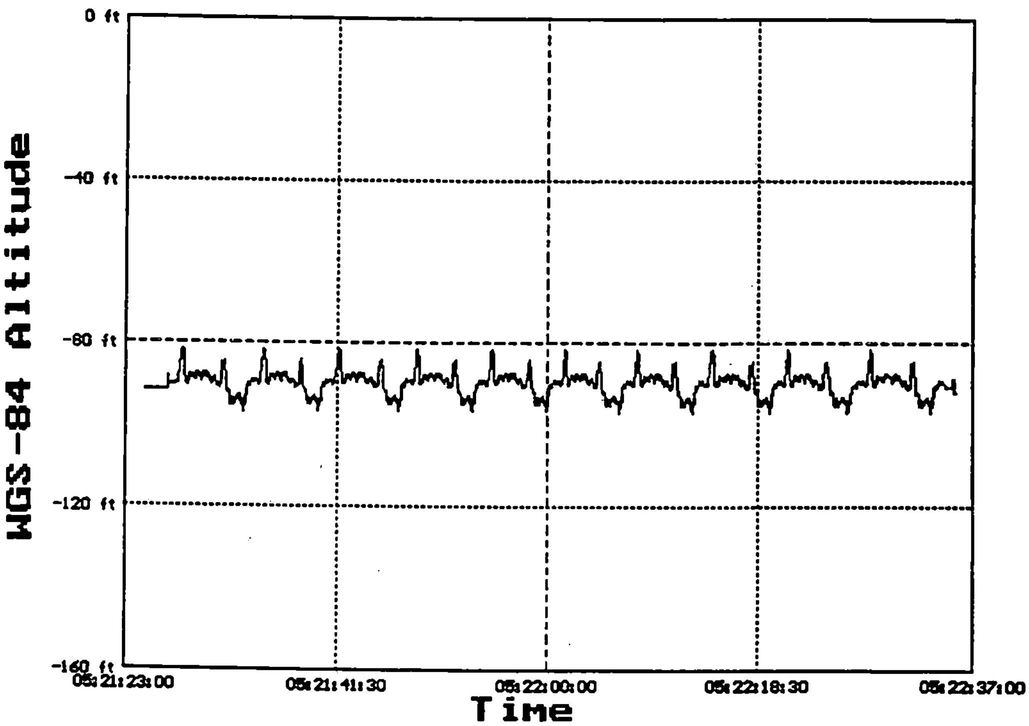

Figure-3 Vertical Profile

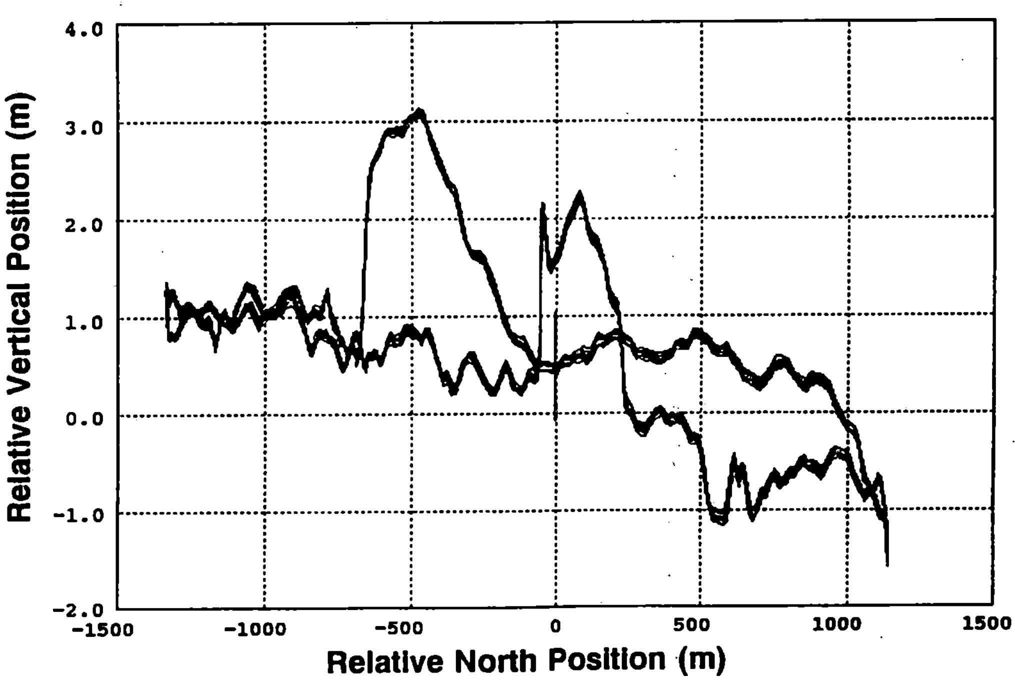

Figure-4 Relative Position: Vertical versus North

Fault-Tolerant Train Positioning for Communication-based Train Control

Milton B. Adams

C. S. Draper Laboratory
Cambridge, MA 02178

(617) 258-3185
adamsm@draper.com

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Fault-Tolerance Systems

- **A fault-tolerant system is able to continue operation in the face of failure, damage, temporary loss or degradation of its component elements**
- **Emphasis is on *continued, non-stop operation***
  - Perhaps at a reduced level of system performance
- **Inherently, a fault-tolerant system is designed to preclude:**
  - *System* loss
  - Exposure of humans to unsafe operational conditions
- **Using the terminology of the rail business, *vital* systems are inherently fault tolerant**
  - The degree of system vitality can be determined through the application of fault-tolerant system design and evaluation methodologies

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Motivation for Fault Tolerant System Design Methodologies

- **Increasing demand for systems providing**
  - High reliability
  - High availability
  - Low operating costs
- **Fault tolerant system design and evaluation require specialized analytical techniques and tools:**
  - Unlike a single-string system, a redundant, fault tolerant system is not simply a "sum of its parts"
  - The implementation of the system architectural (the components and how the are connected) and associated operational rules bear directly on the system's performance
- **A system-level approach is required to model and assess the complexity and subtleties of such a system's behavior**

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Fault Detection, Isolation, & Recovery/Reconfiguration (FDIR)

- **FDIR are integral elements of a fault-tolerant system**
  - Detection and Isolation:
    - ⇨ Detect and determine source(s) of aberrant system behavior
  - Recovery/reconfiguration:
    - ⇨ Given knowledge of the source of faulty behavior, choose a strategy to eliminate or alleviate the effects of the fault
- **FDIR functions must be performed in an uncertain environment**
    - ⇨ Sensor and/or plant disturbances
    - ⇨ Failure mode uncertainty
    - ⇨ Model uncertainty
- **Successful FDIR / fault-tolerance requires some degree of component redundancy**
  - Direct hardware redundancy
    - ⇨ Replicate like-components
  - Analytic redundancy
    - ⇨ Use analytical relationships to create functional redundancy from dissimilar components

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Design Issues / Tradeoffs

- **Nature of redundancy**
  - Direct vs. analytic
- **Degree of redundancy**
  - Number of replications vs. quality of individual components
- **Design of tests for failure detection and identification**
  - Static vs. dynamic
  - Missed failures vs. false alarms
- **Design of decision logic for system recovery/reconfiguration**
- **Building a system-level model that provides the insight that allows systems designers to make the appropriate trade-offs in resolving these issues**
  - **Objective**: Incorporate modeling and evaluation *early* in the design process to provide timely feedback

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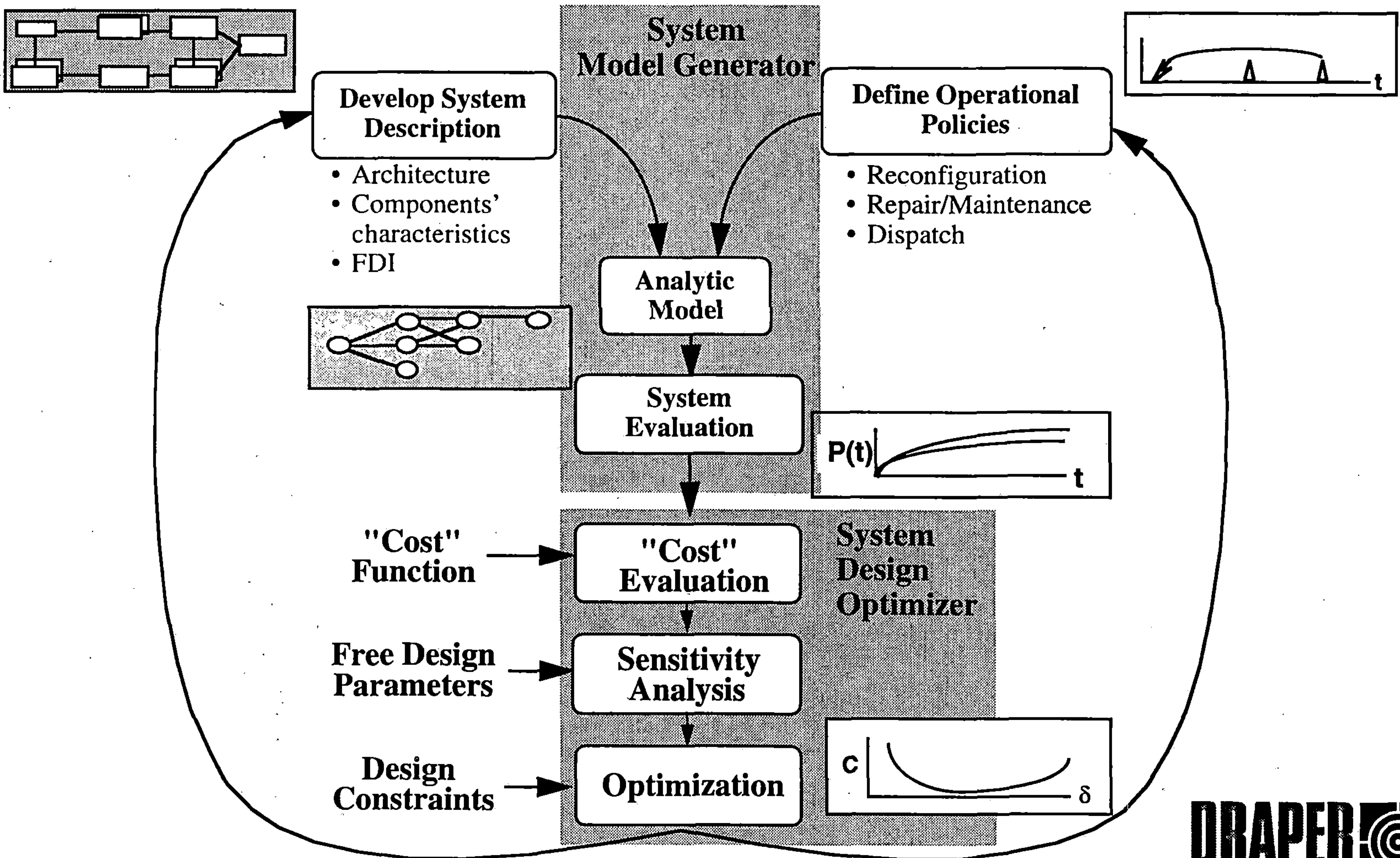
Fault-Tolerant System Integrated Design Process



Types of Analyses

- **Quantitative system evaluation helps guide the design process**
  - Highlights system drivers relative to metrics of interest
  - Aids decision-making in the absence of firm parameter values
- **System evaluation metrics**
  - Reliability
  - Availability
  - Safety and risk
- **Operational policy evaluations**
  - Maintainability
  - Repair and sparing
  - Conditional dispatch (dispatch with failures)
- **Optimization metrics**
  - Life-cycle-cost
  - Mission "utility"

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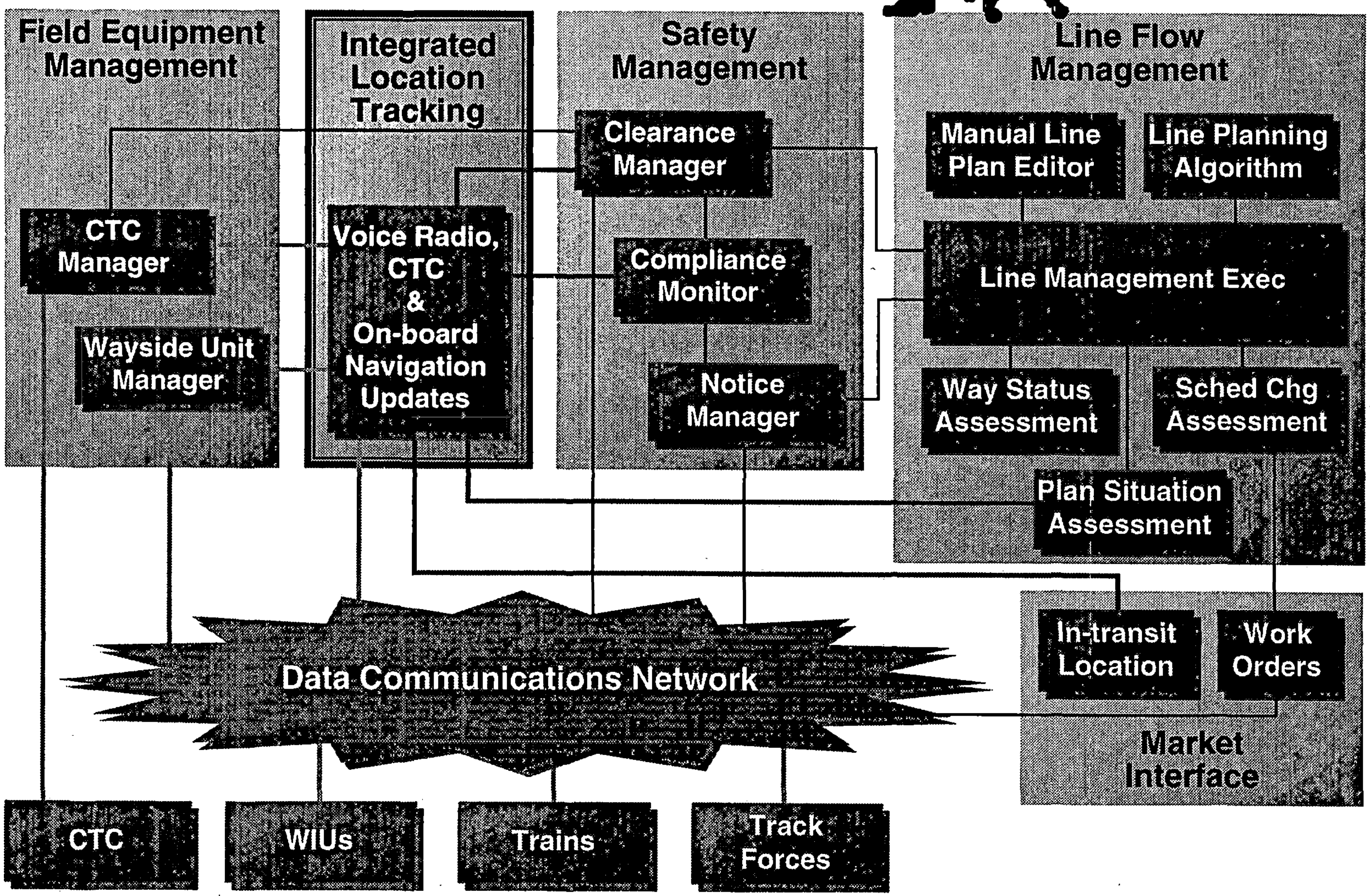
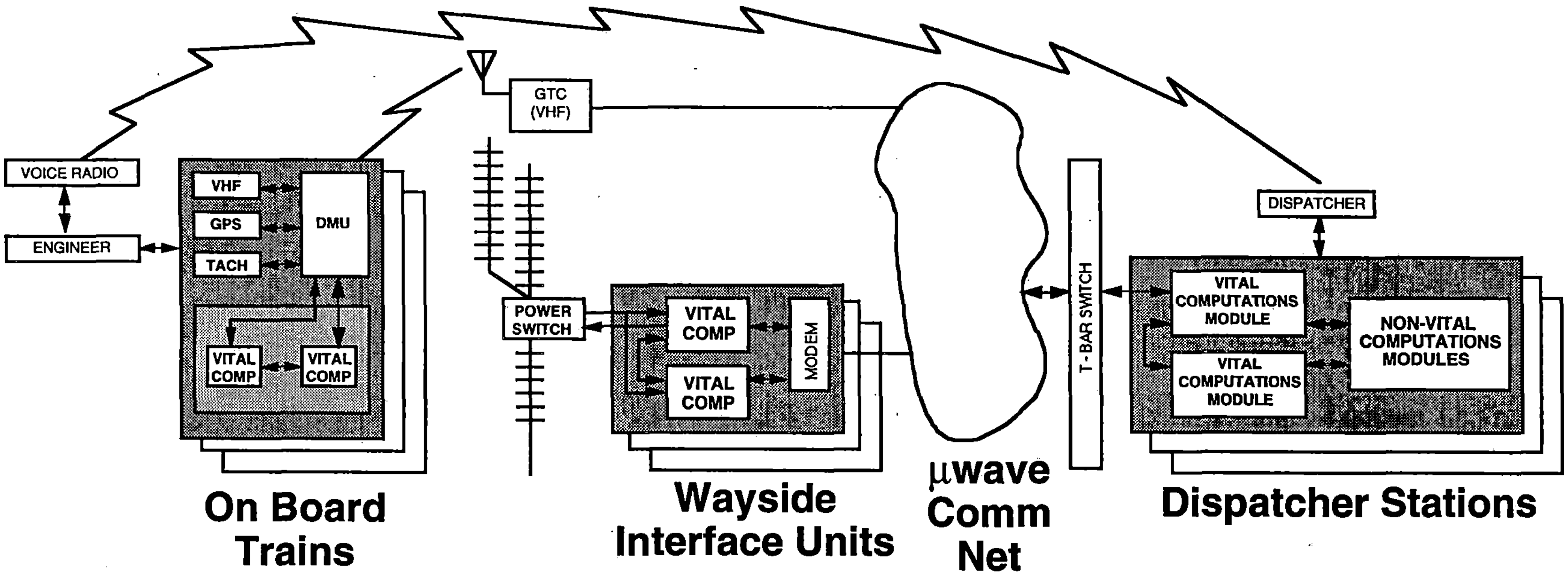
Line Operations: A Functional Model



Notional System Architecture



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Functional Requirements: Train Positioning

Train positioning information is required for:

- **Safe operations: Authority generation and execution**
  - Track resource allocation
  - Track resource de-allocation
  - Execution of clearances
    - On board
    - Wayside
- **Efficient operations: Command and control**
  - Line planning
  - Line plan progress monitoring
- **System-level information: Line operations status**
  - Inter-line coordination
  - Line-yard coordination
  - Customer feedback

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Fault Tolerance in Train Position Sensing

- **Approaches to train positioning sensing**
  - GPS: Standard SA vs. differential vs. carrier phase tracking
  - Mix and match of:
    - ⇨ Inertial sensors: full 6-DOF low cost/micromechanical, heading gyro
    - ⇨ Wheel tachometer
    - ⇨ Switch position information
    - ⇨ “Landmark” ID
      - Wayside transponders
      - Automated wayside feature recognition
      - Digital track map
- **Position sensing redundancy can be achieved by combinations of direct and/or analytic redundancy**
- **System-fault tolerance also requires redundancy in the other components of the system as well**
  - On board
  - Office
  - Wayside
  - Communications

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System Design Issues

- **System must be designed to detect, isolate and reconfigure in a manner that**
  - ❑ Position errors due to component failure/degradation/loss are unable to impact system safety
  - ❑ Upon reconfiiguration, explicit knowledge of
    - ⇨ Position accuracy
    - ⇨ Rate of position reporting

    is know to all system functions using position information
- **Operational procedures must be designed to accommodate variable**
    - ⇨ Position accuracy
    - ⇨ Rate of position reporting

  due to variations in equipage and failures/degradation

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Summary

- The train positioning system comprises more than simply the position sensing equipment, e.g., GPS
- Due to the safety-critical nature of position information, communication-based train control systems must be designed to be fault tolerant
- Fault-tolerant system design involves a huge number of trade-offs that are best addressed through a well-defined fault-tolerant system design methodology

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Current Requirements for Railroad GPS Use

GPS Technical Symposium

November 14, 1996

Howard G. Moody
Association of American Railroads

Questions to ask - Location Determination

- What are the applications?
- What are the requirements including accuracy?
- What are the tools available to meet the requirements?
- What are the costs?

Applications

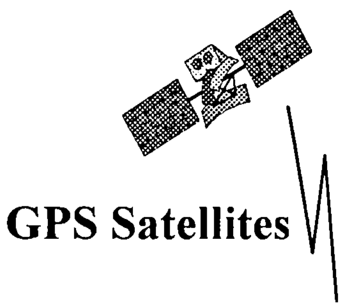
- Current
  - Surveying - including track, facilities, real estate, etc.
  - Location reporting for equipment monitoring
- Future
  - Train monitoring
  - Train control
  - Fiber optic cable location

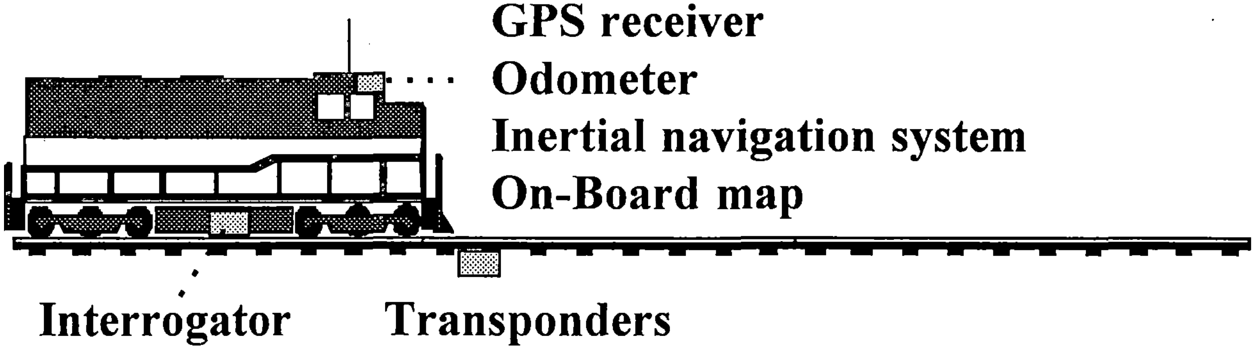
Requirements

- Surveying
  - For track - sub meter
  - Microwave antennas +/- one foot elevation
  - Real estate - local law
  - Fiber optic - 3 feet
- Dynamic location
  - Equipment monitoring - 300 feet
  - Train monitoring - 300 feet

Requirements - Train Control

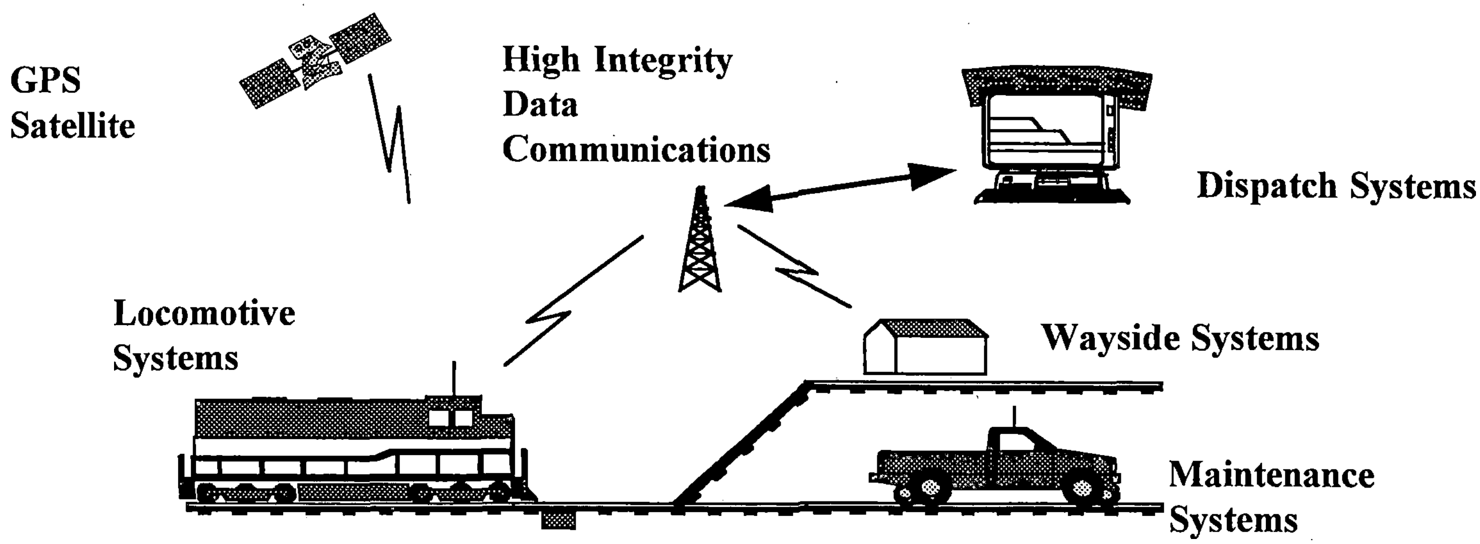
- Location system must:
  - Distinguish parallel tracks
  - Know train's exit from switch
  - Meet latency requirements





Positive Train Separation

- SAFETY IS CRITICAL
- Must demonstrate improvement over existing systems
- Designed for railroad operating environment



Tools

- Location systems
  - Standard surveying equipment
  - GPS, GLONASS, other radio ranging technology
  - Transponder/interrogator
- Data bases - geographic information systems
  - Computer files and data bases
    - e.g. AutoCAD, Mapinfo and TIGER files

Technical Issues

- Location determination system
  - Accuracy - from sub-meter to 300 feet
  - Reliability & maintainability
  - Coverage - are all switches covered?
  - Data integrity - is the received information correct?
  - Safety system calibration
  - Failure modes

Technical Issues

- Data base
  - Accuracy of location information
  - Indices and integrity
  - Standards - e.g. geographic referencing standards
  - GIS mapping system - allows derivative products

WIDE AREA DIFFERENTIAL GNSS DEMONSTRATION

LOCKHEED MARTIN

IRAD OVERVIEW

Objective: Develop a GPS wide-area corrections testbed to 1) validate our methods and algorithms 2) ensure they work in real time and 3) provide a platform for increasing customer confidence in our solutions.

PHASES

I. Correction algorithm software generation. Static testing with data from Ashtech and E-Systems. 1Q95-2Q95

II. Installation of 5 Loral GPS monitoring sites and static testing with data from those sites. 2Q95-3Q95

III. Integration of software for real-time operation using the 5 Loral GPS monitoring sites and testing. 4Q95

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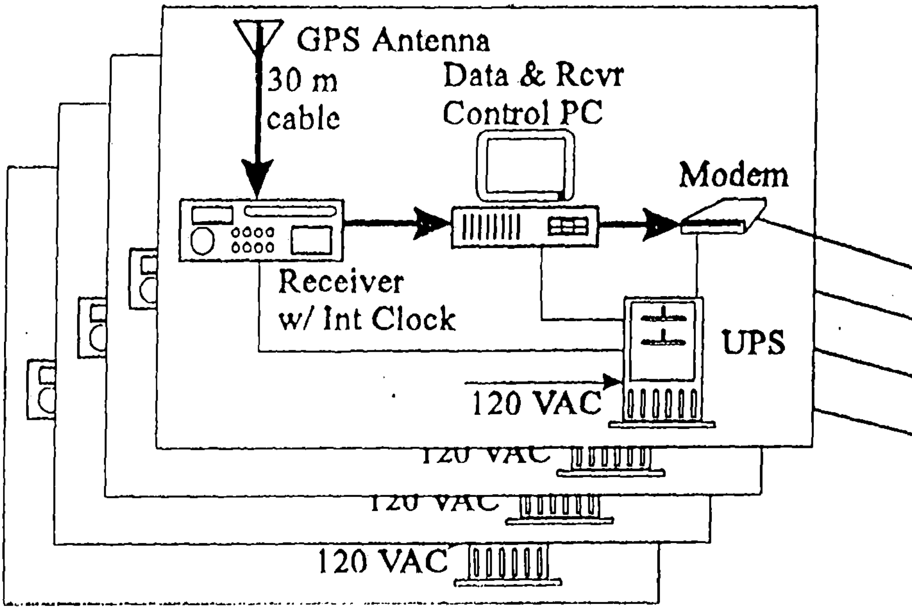
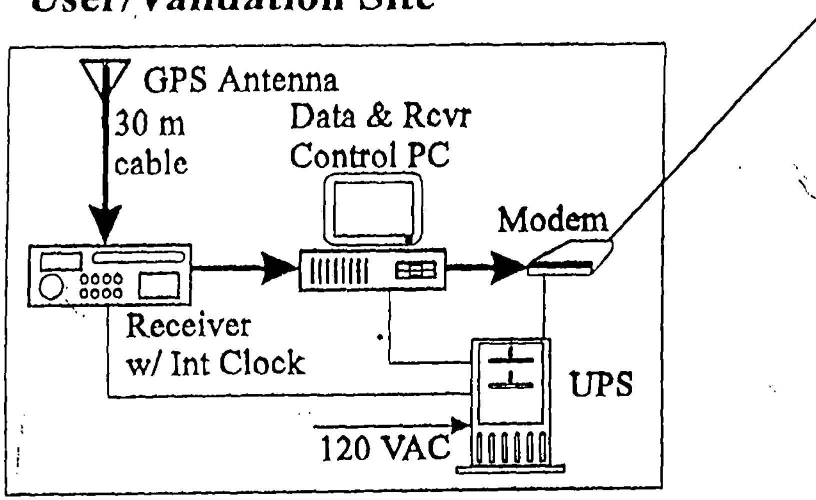
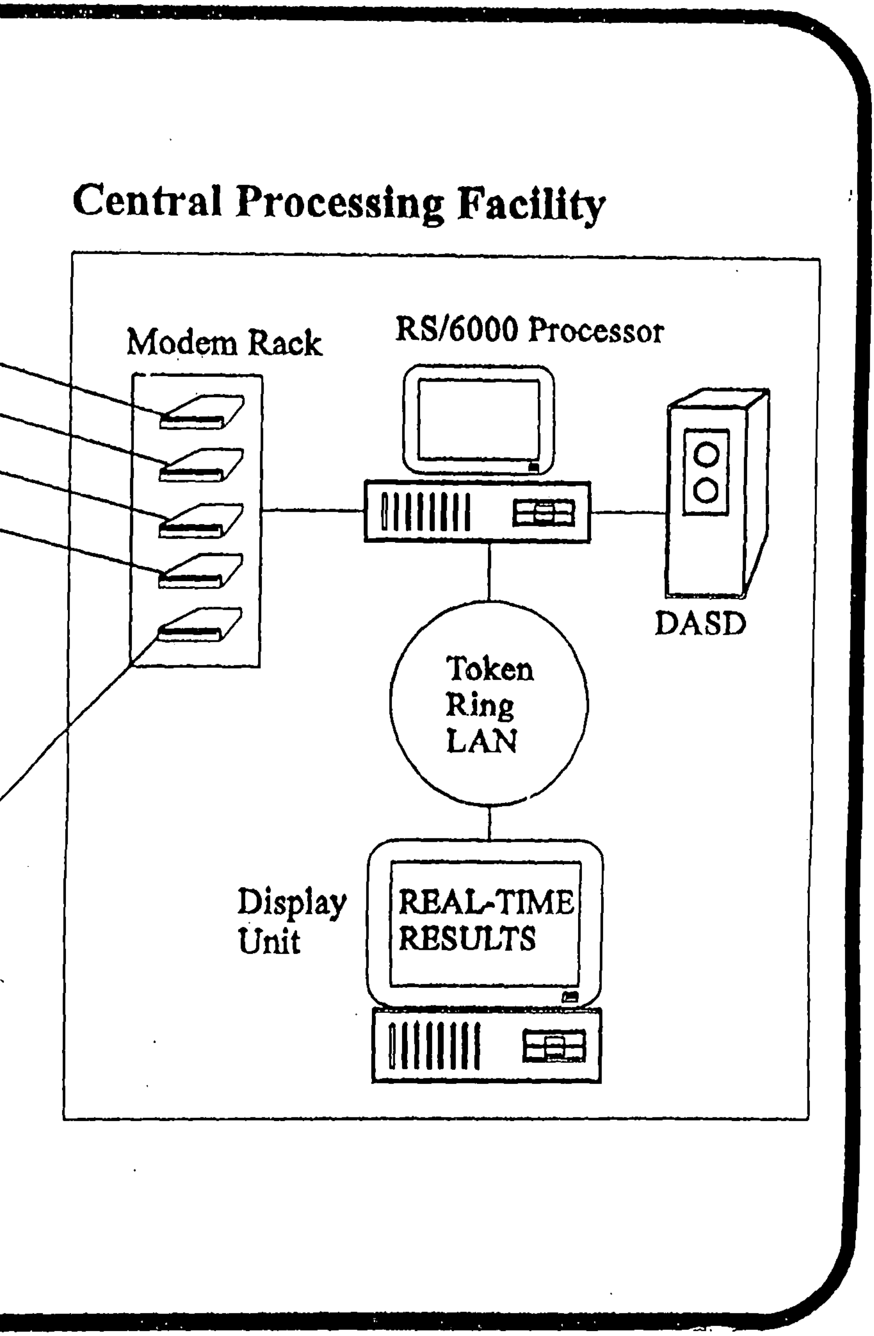
Monitor Sites



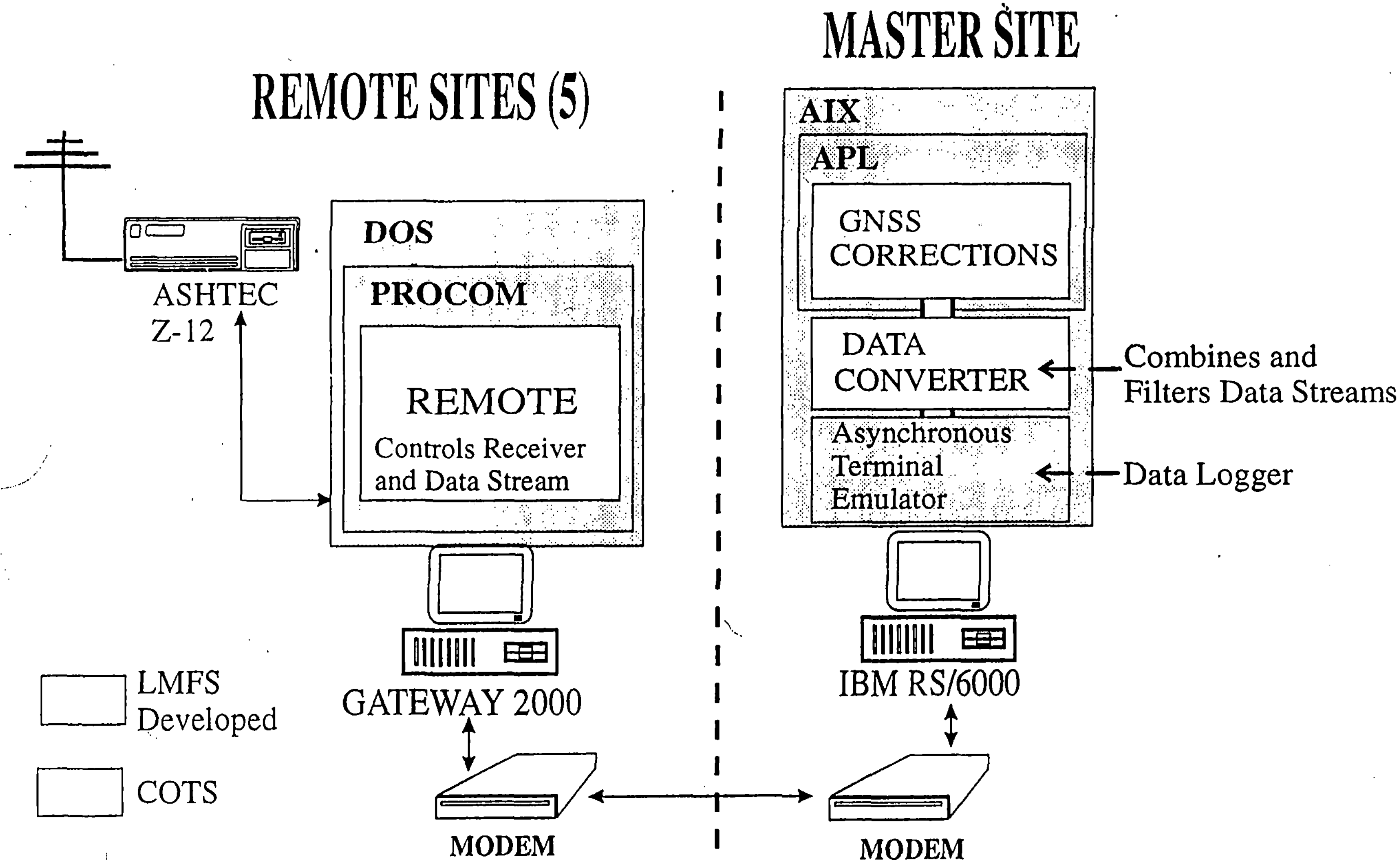
User/Validation Site




Central Processing Facility
Modem Rack
RS/6000 Processor
DASD
Token
Ring
LAN
Display
Unit
REAL-TIME
RESULTS

GNSS System Software Architecture

PROVIDES REAL-TIME GPS CORRECTIONS



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TEST OBJECTIVES

SHOW SYSTEM STABILITY UNDER ALL CONDITIONS

TEMPORAL STABILITY

•Show solution is **stable across time** (i.e.., stable across differing satellite geometries and atmospheric conditions).

SPATIAL STABILITY

•Show solution is **stable across space** (i.e.., stable across varying user locations)

TEMPORAL STABILITY CONDITIONS

POOR GEOMETRY, EXTRA LATENCY

- Static user located in Akron, OH, 400 miles from nearest monitor site
- Monitor sites: Gaithersburg, MD; Owego, NY; Scranton, PA; Atlanta, GA
- 24 hour test
- Intentional 10 second latency added

TEMPORAL STABILITY RESULTS

VERTICAL ERROR ONLY 2.8 METERS 95% OVER 24 HOURS

Data collected over 24 hours on November 12-13, 1995

GNSS USER ERRORS (METERS)

Component	Average	1 Sigma	95%
Horizontal	0.1	0.9	1.7
Vertical	**0.2**	**1.4**	**2.8**
Total	0.2	1.7	3.1

SPATIAL STABILITY RESULTS

LARGE MOVEMENT TEST

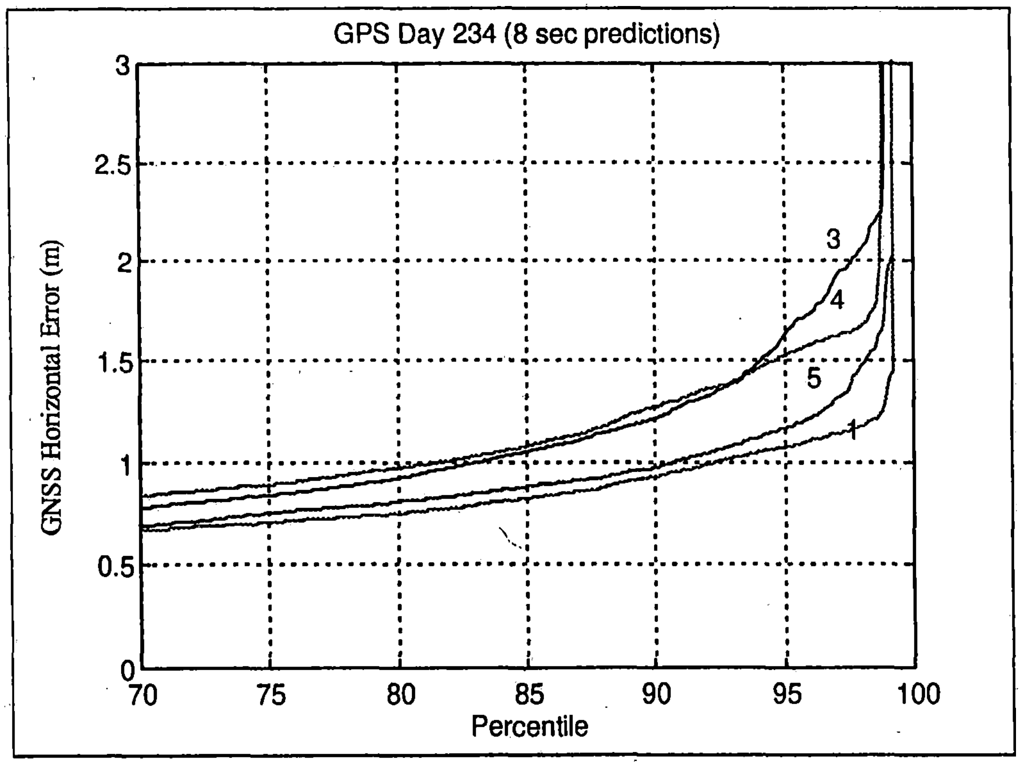
Average 95% Vertical error only 2.5 meters at all locations

- 2 hours of data processed with Akron as the user site
- Same data processed with Atlanta as the user site
- Continued until all 5 sites had been processed as the user

USER LOCATION	95% VERTICAL ERROR
Akron	2.0 meters
Atlanta	3.2 meters
Gaithersburg	3.0 meters
Owego	2.2 meters
Scranton	2.0 meters
Average	**2.5 meters**

LOCKHEED MARTIN
FEDERAL SYSTEMS - GAITHERSBURG

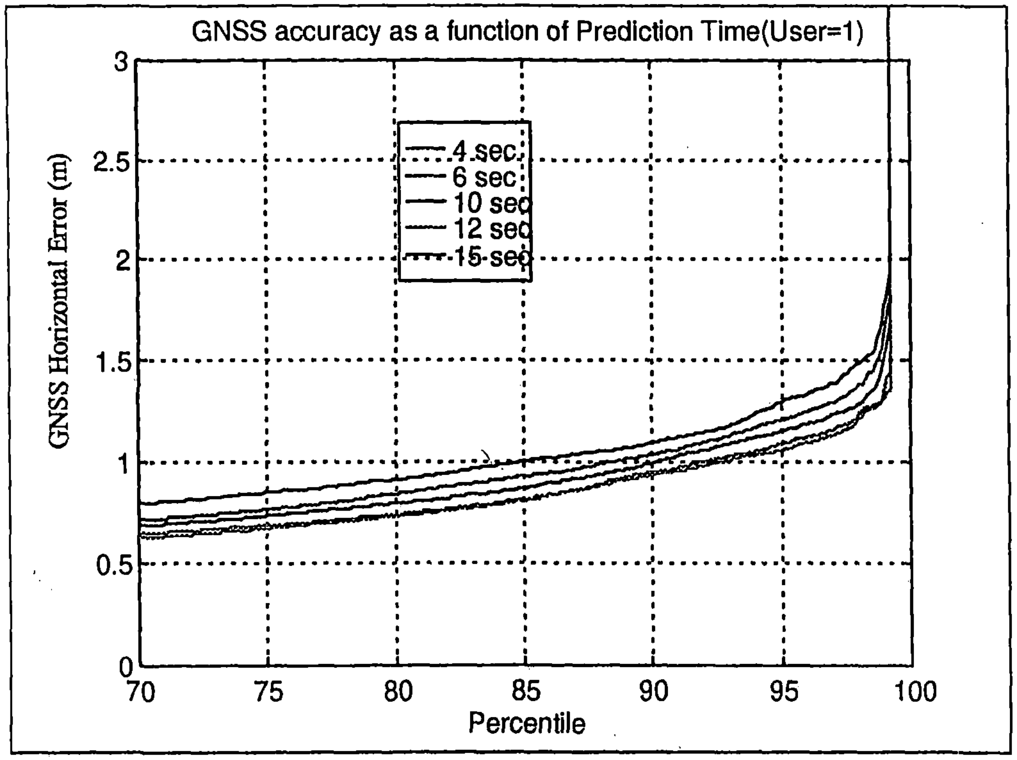
GNSS Accuracy



1 Akron
2 Atlanta
3 Gburg
4 Owego
5 Scranton

LOCKHEED MARTIN
FEDERAL SYSTEMS - GAITHERSBURG

Effect of Latency



ACCOMPLISHMENTS

- **5 OPERATIONAL SITES**

  Gaithersburg, MD; Owego, NY; Akron, OH;

  Atlanta, GA; Scranton, PA

- **SYSTEM OPERATION SUCCESSFULLY DEMONSTRATED**

  Data now being collected and processed

- **ACCURACY CONSISTENTLY UNDER 3 METERS (95%)**

  Accuracy has been tested and found stable over both time and user location

C1 13

Lockheed Martin Wide Area Differential GNSS Testbed Results

Art Gower, Tim Parker and Jack Rudd, *Lockheed Martin Federal Systems*
Henry Beisner, *Paradeigma, Inc.*

Biography

Arthur G. Gower is an Advisory Systems Engineer with LMFS. He received his B.S. in Aerospace Engineering and M.S. in Nuclear Engineering from Virginia Polytechnic Institute. He was the IBM Block II satellite navigation payload engineer and the Loral lead engineer for the Block IIR satellite Control Segment upgrades. He led the GPS Integrity Study for the DoD in 1991, has worked on the WAAS and MTSAT architectures, the GPS Control Segment re-architecture, and led the Loral GNSS wide area corrections testbed effort.

Timothy C. Parker is a Senior Systems Engineer involved in commercial and civil GPS applications. His work focuses on performance analysis of satellite based navigation systems. He led the development of the Lockheed Martin Service Volume Model. He received a B.S. in Mathematics with emphasis in Computer Science from Virginia Commonwealth University and is currently pursuing an M.S. in Systems Engineering at George Mason University.

Jack G. Rudd is a Senior Technical Staff member currently developing and prototyping algorithms for satellite surveillance systems and GPS applications. He received a B.A. in Mathematics from the University of Iowa. He led activities in target detection, tracking, estimation, multisensor data fusion, and the calibration of satellite surveillance sensors using ground-based lasers. He created a large part of the GNSS correction generation software for the testbed and is the author of a number of papers on rapid prototyping of advanced applications.

Dr. Henry Beisner is a consultant to Lockheed Martin on GPS and differential GPS navigation. He is president of Paradeigma, Inc., consulting in applied physics, signal processing and analysis. He spent nine years with IBM developing the GPS Control Segment. He analyzed estimation of orbits and clock biases, proved the validity of the Control Segment coordinate system, developed the orbit integrator standard, and demonstrated that GPS met the user navigation error specification. He received a Ph.D. in Physics from Ohio State University and has authored a number of papers in the field of navigation.

Abstract

Lockheed Martin Federal Systems (LMFS), known as Loral Federal Systems prior to being purchased by Lockheed Martin in 1996, and known as IBM Federal Systems prior to being purchased by the Loral Corp. in 1994, has been the prime GPS Operational Control Segment (OCS) contractor since 1980. LMFS was responsible for the procurement and integration of the GPS Monitor Stations and Ground Antennas. LMFS designed and implemented the majority of software in the GPS Master Control Station, including the Kalman filter that is utilized to estimate and predict the GPS satellite clocks and orbits. LMFS designed and implemented the software necessary to format these predictions into the GPS navigation message. LMFS has recently completed upgrades to the OCS in support of the new Block IIR satellites. As a part of the GPS OCS support contract LMFS will evolve the entire control segment from a centralized host-based system to an open workstation-based distributed architecture.

This wealth of knowledge and experience with the estimation and prediction of satellite orbits and clocks, as well as the design and development of the GPS OCS, has provided a solid foundation for developing a wide area differential correction GPS navigation system. It is this core of knowledge and experience that has fueled the Independent Research and Development (IRAD) program for the LMFS Wide Area Differential Global Navigation Satellite System (GNSS) testbed.

The GNSS IRAD program has three goals:

1) validate the design and accuracy of our algorithms,
2) ensure that the corrections may be continuously determined in real time, and
3) demonstrate that the accuracy achieved, when applying these corrections, exceeds the requirements for Category I Precision Approach (CAT-I).

All three of these goals have been achieved and repeatedly demonstrated in our Wide Area Differential GNSS Testbed.

This paper will describe the results obtained using the testbed from two perspectives. First, an analysis of the Service Volume is presented for locating the testbed monitoring sites. This analysis uses the LMFS Service Volume Model (SVM), a high fidelity covariance-based analysis tool used to determine user obtainable navigation accuracy and service availability.

As a second perspective, this paper presents actual results obtained when using the Wide Area Differential GNSS Testbed. The testbed consists of 5 GPS monitoring sites including a central processing capability all located in the Eastern portion of the United States. The results represent both temporal and spatial tests and comparisons are made to the results predicted by the SVM.

Introduction

We have witnessed a dramatic growth of the GPS from a concept to a test system to an operational system in slightly over a decade. We are now witnessing an explosion of applications, new and old, that depend upon the GPS being maintained as a stable global utility. The breadth of applications are further enabled through augmentation of GPS. Wide Area Differential systems offer improved accuracy, integrity, and availability to GPS users within their service volume. The LMFS expertise in clock and orbit determination and generation of the GPS navigation message that were gained in developing and upgrading the GPS Control Segment are directly applicable to a wide area differential correction system.

LMFS performed many internal studies and designs in order to support our proposal to the FAA for the Wide Area Augmentation System (WAAS). We developed the architecture, performed requirements definition, and developed the wide area differential correction algorithms and our SVM in anticipation of performance on a program with a very tight schedule. These efforts were then continued with IRAD funding. The program completed to date had three phases.

Phase I

- Generation of software containing our wide area differential correction algorithms.
- Use of the SVM to select monitoring sites.
- Use of the SVM to predict the performance of the testbed under a variety of conditions and assumptions.

Phase II

- Installation of the hardware for the 5 GPS monitoring sites.
- Static testing with GPS observations from the 5 sites.

Phase III

- Integration of software for real-time operations.
- Real-time system testing for temporal stability (long term tests).
- Real-time system testing for spatial stability (differing user locations).

LMFS created a 5 site wide area differential correction testbed for the purposes of

1) testing the accuracy of our wide area differential corrections methods and algorithms,
2) validating that the corrections can be continuously determined and applied in real time, and
3) demonstrating that the accuracy achieved, when applying these corrections, exceeds the requirements for Category I Precision Approach (CAT-I).

The system uses Standard Positioning System (SPS) C/A code measurements from 4 of the 5 monitor sites to determine the wide area corrections. After generation of the corrections, an adjustable time delay is applied to account for transmission of the corrections to the user. This delay is set very conservatively between 8 and 10 seconds.

The corrections are then applied to the current measurements at the fifth site, which is used as both a known user location and an integrity monitor. Statistics are generated and the user location error is displayed.

Site Location Selection

Several site locations were considered for deployment of the GNSS testbed GPS receivers. Most sites were conveniently collocated with an existing company facility. Taken together, the site combinations were evaluated as a location set. Different sets, or combinations of the sites, were evaluated using the SVM to determine if there would be a significant effect on the expected GNSS testbed performance. The results as summarized in Table 1, contain 2-Sigma values representing the SVM prediction for average Vertical Position Accuracy (VPA) and average Horizontal Position Accuracy (HPA) as well as the average user error, where user error is defined as:

$$UserError = \sqrt{(VPA)^2 + (HPA)^2}$$

Coverage represents the percent of evaluated grid points where the predicted accuracies are less than the required threshold value of 7.6m [1].

Table 1. SVM Site Location Analysis Summary

Set	VPA	HPA	User Error	Coverage	Sites
1	7.013	7.358	5.082	84%	O,G,Ak,At
2	6.871	7.219	4.983	36%	O,G,Ak,N
3	6.837	7.187	4.960	36%	O,G,Ak,S
4	6.829	7.176	4.953	84%	O,N,Ak,S
Site Key		Location			
Ak		Akron, OH			
Ar		Atlanta, GA			
G		Gaithersburg, MD			
N		Norfolk, VA			
O		Owego, NY			
S		Scranton, PA			

The objective of the selection analysis is to optimize the site locations. This involved minimizing deployment cost (not shown in the table), while maximizing coverage and minimizing user error. Although set 4 meets the objectives of maximum coverage and minimum user error, it had a high deployment cost due to usage of non-company property. Set 1 was selected because it offered a reasonable geometry for determining wide area corrections, had good coverage, and offered a smaller deployment cost.

Aside from the measures of position accuracy, another particularly good indicator for assessing the navigation accuracy attainable from a wide area differential GPS design is that of the User Range Error (URE) [2].

URE depends on three error sources: Space Vehicle (SV) ephemeris error, SV clock estimation error and SV clock dither prediction error, i.e., Selective Availability (SA) [3; 4; 5]. Given a set of monitoring stations, satellites and the pseudorange measurements between them, one can estimate the SV ephemeris and SV and Monitor Station clock biases [5; 6]. The estimation of GPS SV ephemerides is well understood once the SV clock bias is removed from the problem [7]. URE has been shown to be related to the total number of Monitor Stations and the pseudo-measurement error. [2].

Service Volume Model (SVM) Simulations

Three SVM simulations were prepared for evaluating the predicted performance of the testbed. Figure 1 shows the expected accuracies achievable by the LMFS wide area differential testbed (prior to calibration with test data). Figure 2 uses the same grid area as Figure 1, but the wide area differential performance parameters have been calibrated with testbed operational results. Figure 3 also uses the calibrated parameters of Figure 2 but looks at the testbed performance over a much larger area.

The simulations modeled the 24 satellite GPS constellation using satellite almanac data available from the U.S. Coast Guard Electronic Bulletin Board input directly to the SVM. The satellite orbits for a complete sidereal day were modeled at time increments of 300 seconds for Figures 1 and 2 and 60 seconds for Figure 3.

The coverage areas evaluated were based on a lattice of grid points spaced at 2.5°. At each grid point and for each time point, the SVM evaluates the navigation position solution accuracy that a user can expect to achieve when applying wide area differential corrections.

The SVM simulation results are summarized in Table 2. Note that the Vertical Position Accuracy (VPA) and Horizontal Position Accuracy (HPA) are averaged over every grid point, many of which are outside of the viable Service Volume for the testbed. Actual performance within the Service Volume will be better than that indicated.

Table 2. SVM Simulation Results

Figure #	Inputs	VPA	HPA	User Error	Grid Size
1	Uncalibrated	7.66	7.9	11.02	144
2, 3	Calibrated	3.05	2.39	3.87	144

The results shown in Figure 1, based upon uncalibrated assumptions, predict that the testbed should be capable of meeting the CAT-1 precision approach requirements of 7.6 meters for VPA and HPA everywhere within the applicable Service Volume (smaller than that shown in the Figure).

The results shown in Figures 2 and 3, calibrated to reflect actual testbed operations, demonstrate that the testbed is capable of meeting the VPA and HPA requirements for CAT-I precision approach over a much larger area than originally anticipated. All accuracy measurement values are shown in meters 2-sigma unless indicated otherwise. The graphics utilize a color bar, reproduced here in gray-scale, to indicate the predicted accuracy attainable, on average, at each grid point location. The scale range shown is from 0 to 10 meters, 2 sigma.

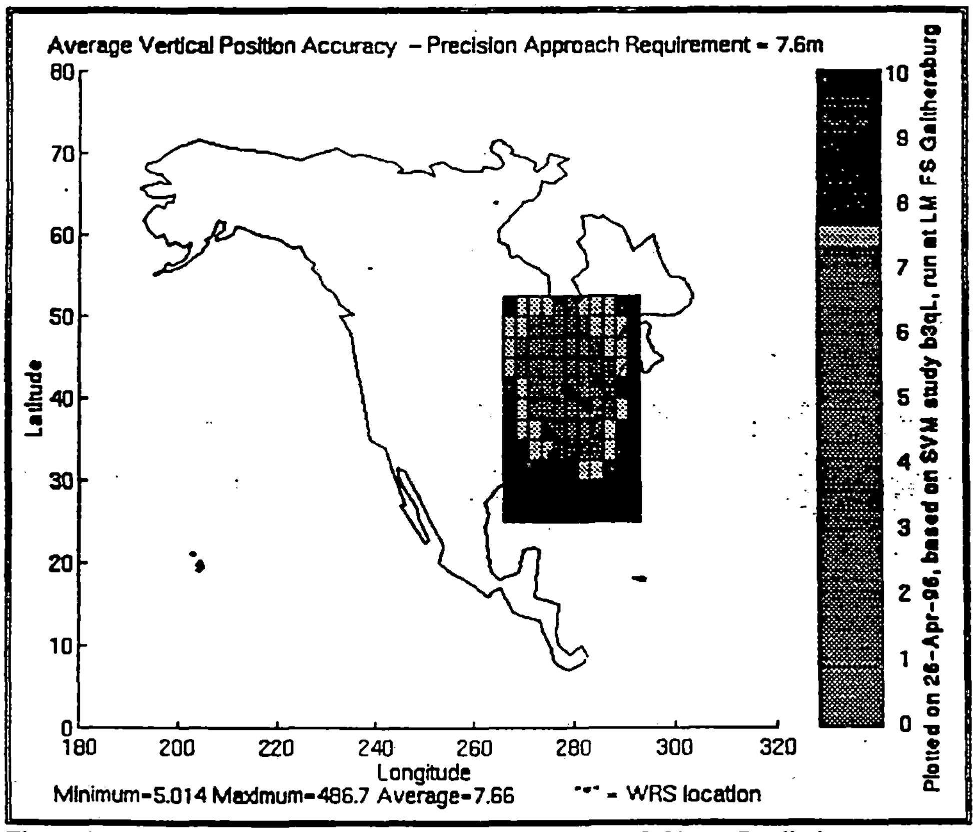


Figure 1 - Uncalibrated Service Volume Vertical Accuracy 2-Sigma Prediction

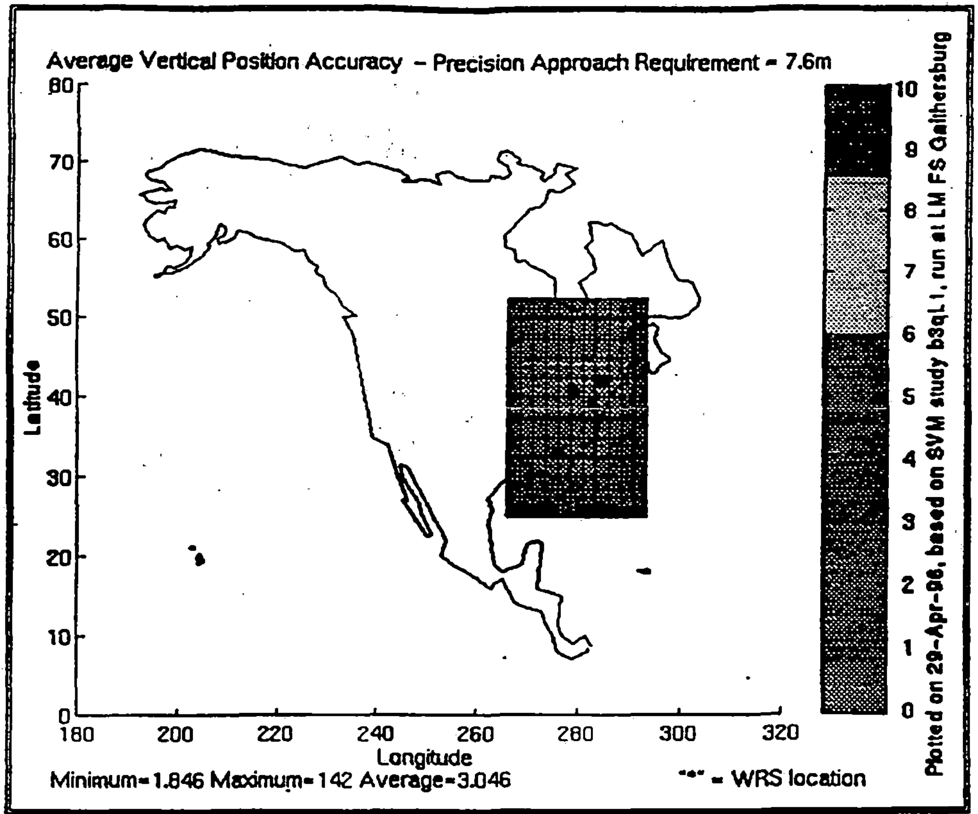


Figure 2 - Calibrated Service Volume Vertical Accuracy 2-Sigma Prediction

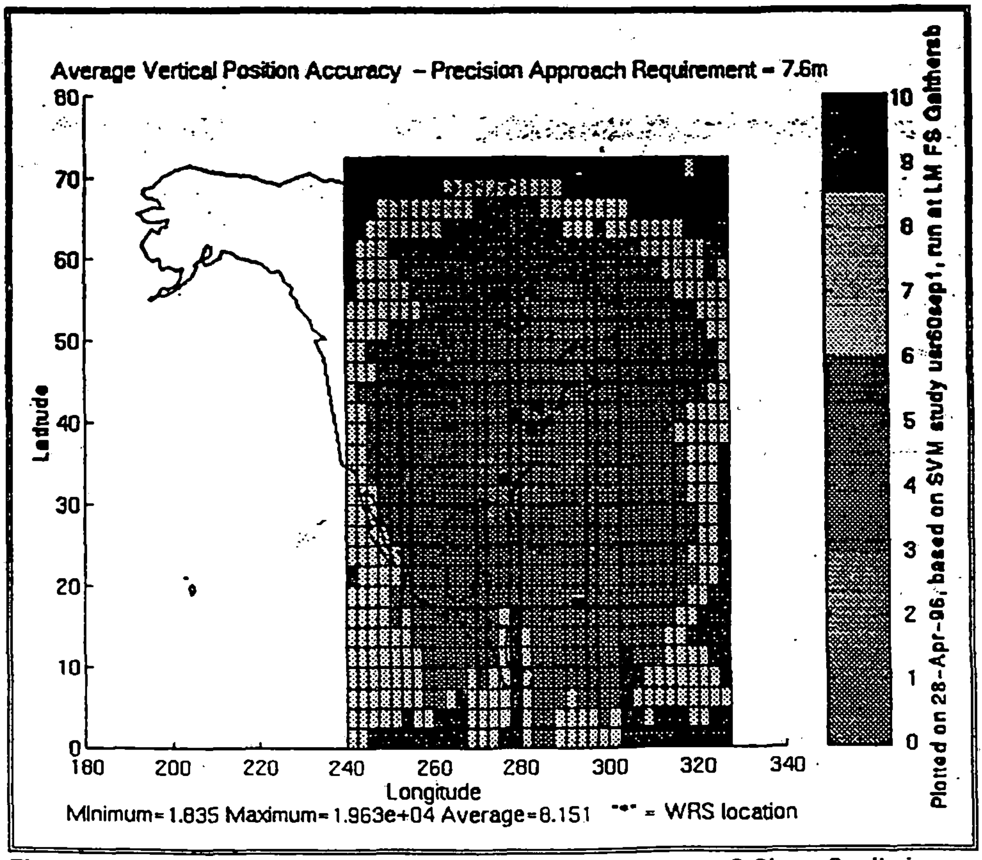


Figure 3 - Extended Calibrated Service Volume Vertical Accuracy 2-Sigma Prediction

Hardware Configuration

LMFS set up a network of 5 GPS monitoring sites (MSs) and a Central Processing Facility (CPF). The CPF is located in the LMFS facilities in Gaithersburg, Md. The 5 MS locations are:

1. Lockheed Martin Federal Systems, Owego, New York
2. 'Lockheed Martin Tactical Defense Systems, Akron, Ohio
3. Lockheed Martin Tactical Defense Systems, Scranton, Pennsylvania
4. Lockheed Martin Federal Systems, Gaithersburg, Maryland
5. Lockheed Martin Display Systems, Atlanta, Georgia

These site locations are shown in Figure 4.

The hardware design of each MS is shown in Figure 5. Each MS has a GPS antenna (choke ring), 12-channel receiver, PC, Uninterruptible Power Supply (UPS), and a modem.

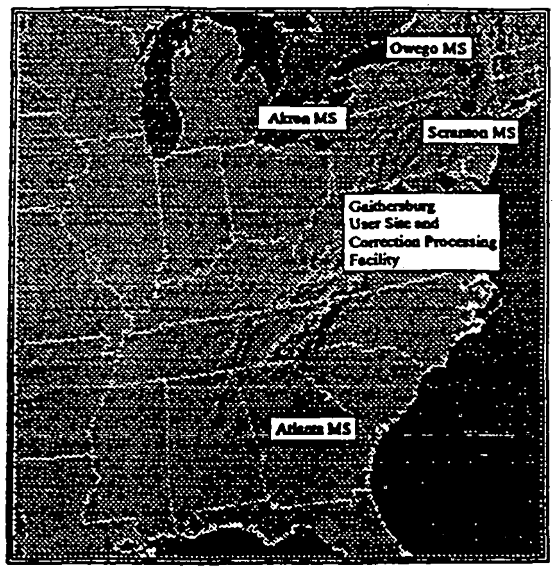


Figure 4 - MS and CPF locations

The receiver is an Ashtech Z-12. We replaced the factory crystal oscillator with a more stable crystal to improve the measurement performance.

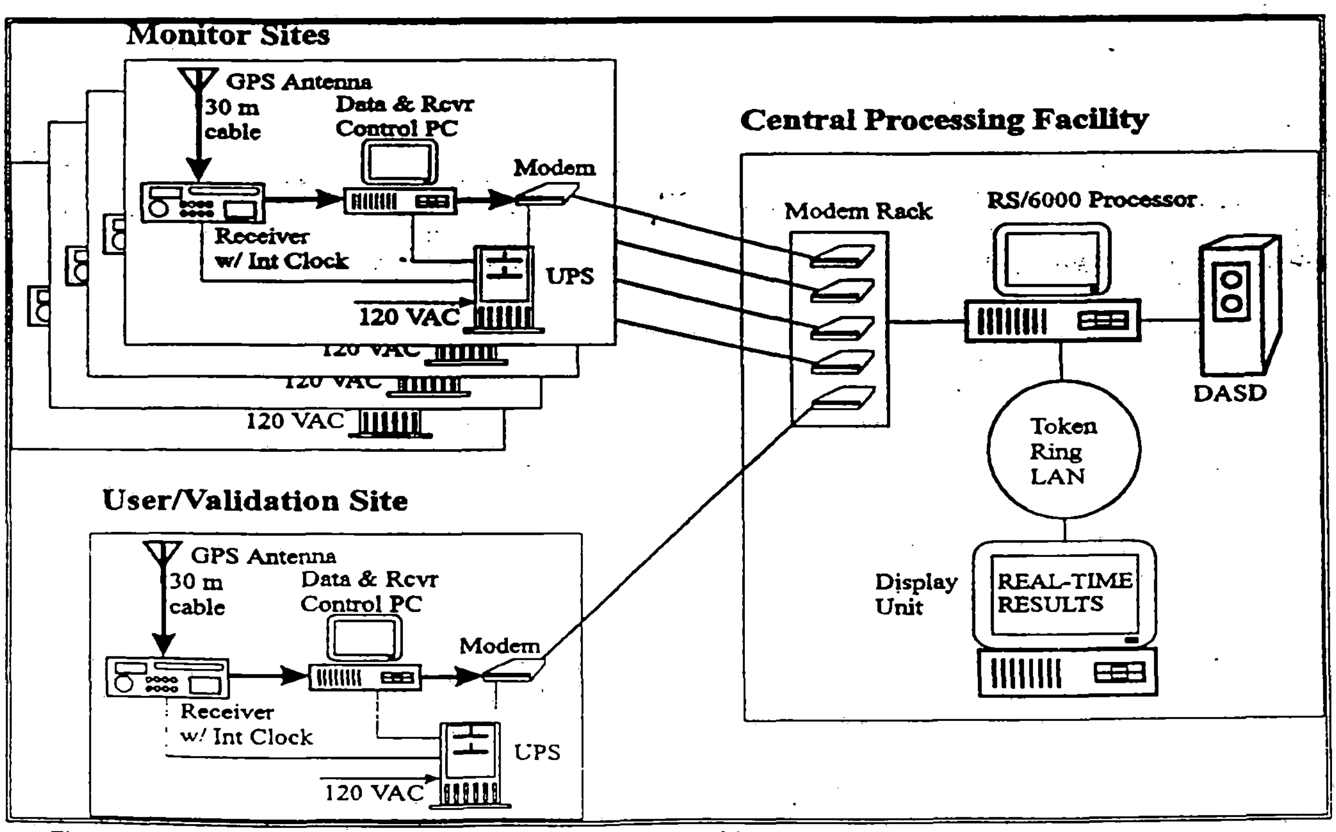


Figure 5 - GNSS Wide Area Correction System Hardware Architecture

We found the performance of the Ashtech Z-12, with the upgraded clock and jitter correction, to be exceptional, with very low noise and very good multipath rejection. All of the Monitor Sites used crystal oscillators except for the Gaithersburg MS, which has a Rubidium frequency standard.

The Central Processing Facility consists of a modern rack, an IBM RISC/System 6000 model 580 and a display unit. The 580 is connected to the LMFS Gaithersburg internal LAN and can be controlled from any compatible workstation. The accuracy graphs and statistics can also be displayed on any compatible workstation. We intend to make this control and display function remotable in the near future.

Software Configuration

The GNSS correction generation software was written during Phase I of the project, tested with static observation data in Phase II, and tested with real-time data in Phase III. The communications software was written and tested in Phase III.

The correction generation software is written in an engineering prototyping language [8,10] to enable rapid evaluation of different algorithms. The communications software is written in C.

A block diagram of the correction generation software is shown in Figure 6. A variable delay was inserted between the generation of corrections and their use by the user to simulate communications and other delays. During our testing, we set this delay at a very conservative value of 10 seconds (the equivalent delay for the FAA WAAS is approximately 2.5 seconds).

Software to provide corrections to the GPS orbital parameters is available but has not been needed. Instead the GPS navigation message was used as broadcast. The software to provide corrections to the orbital parameters will be implemented in an operational system. It was not needed for the testbed because excellent system accuracy was obtained without it.

The communications software for the monitoring sites included the communication product PROCOM and software written by LMFS to control the Ashtech Z-12 receiver and format the data stream back to the Central Processing Facility. At the CPF, data logging was provided by the Asynchronous Terminal Emulator (ATE) and data conversion and coordination was performed by the LMFS Data Converter. The LMFS Data Converter receives data streams from all five monitor sites, combines the data and places it onto "named pipes" for subsequent use by the correction generation software as shown in Figure 6.

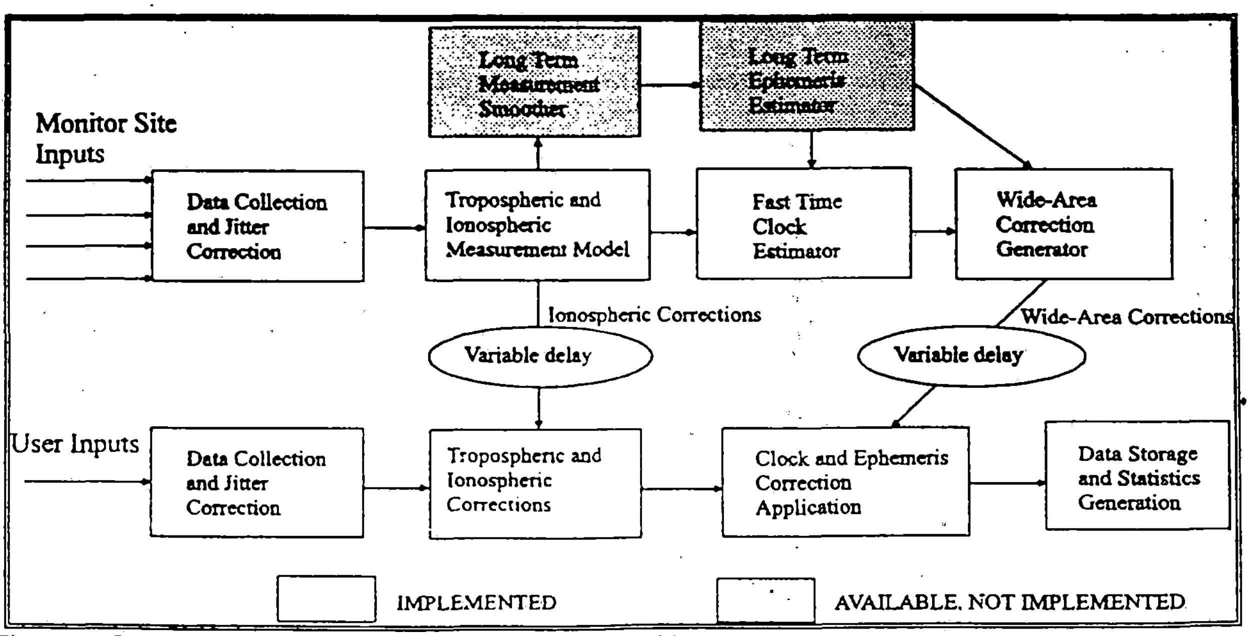


Figure 6 - GNSS Wide Area Correction System Software Architecture

C/A Code Test Results

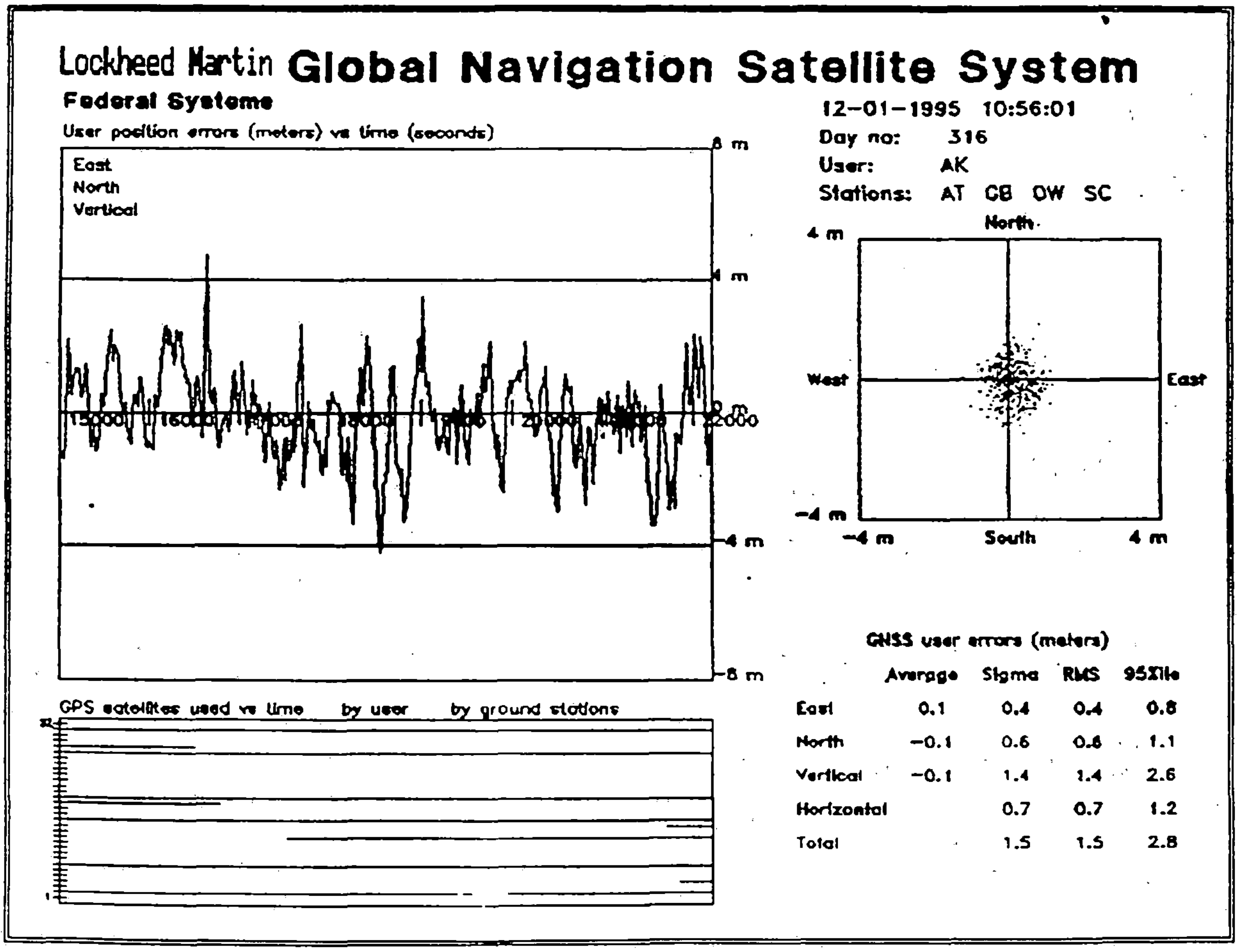
Wide area differential corrections are calculated based on C/A code data from the four Monitor Sites and, after a database specified delay, are applied to C/A code data from the fifth station (the user/validation station). Errors at the user location are calculated and displayed in real-time. Data taken from October of 1995 through March of 1996 has verified the temporal stability and spatial consistency of the wide area corrections.

The tests demonstrate remarkable user location accuracies. With the correction messages of this system, accuracies of better than 3 meters vertical, at 95 percentile, have been routinely obtained. This is significantly less than half the WAAS specification of 7.6 meters vertical user error, at 95 percentile.

Temporal Stability

To demonstrate temporal stability, one must show that the calculated locations, based on the differential correction messages, are stable across time, e.g., stable across differing satellite geometries and atmospheric conditions. The One Day Test demonstrated continuious stability for 24 hours as well as stability over the 18 day period since the station locations were surveyed.

Twenty four hours of data were taken on 12 November 1995. The Akron station was designated as the user, with a 10 second latency in the corrections, i.e., 10 second predictions. The first two hours of vertical and horizontal location errors are plotted in Figure 7.



	Average	Sigma	RMS	95%ile
East	0.1	0.4	0.4	0.8
North	−0.1	0.6	0.6	1.1
Vertical	−0.1	1.4	1.4	2.6
Horizontal		0.7	0.7	1.2
Total		1.5	1.5	2.8

Figure 7 - Two Hours of 24-Hour Test [Note The figure is a composite of 4 plots; Vertical error, shown at upper left, Satellites used shown at lower left, Horizontal error scatter at upper right, and statistics.]

Referring back to Figure 4, it should be noted that the corrections geometry with Akron designated as the user/validation site is very poor. Akron is outside of the service volume of the system. Even so, the detailed time dependency of the vertical error is almost entirely contained within 4 meters. The horizontal error scatter plot is even more tightly grouped.

The full 24 hours of location errors are plotted in Figure 8 which consistently retains the character of the first two hours. The vertical error is 2.8 meters, at 95 percentile. The horizontal error is 1.7 meters, at 95 percentile. These are well within half of the WAAS specification of 7.6 meters vertical and 7.6 meters horizontal, at 95 percentile. Note, also, that Akron is over 260 miles from the nearest monitor site and outside of the monitoring area of the remaining stations.

Spatial Consistency

To demonstrate spatial consistency, one must show that the calculated locations, based on the differential correction messages, are consistent for various user positions. A small and a large movement test was performed.

For the small movement test, the Gaithersburg GPS antenna was moved 7.9 meters South and 3.9 meters East. This movement was measured precisely and the measurements were incorporated into the station location database. Data was taken on 4 December 1995 after the antenna movement and database change. Gaithersburg location errors, based on this data, are plotted in Figure 9. The errors were determined for a latency, i.e., prediction delay, of 8 seconds.

The statistics (lower right corner of Figure 9) demonstrate a spatial consistency of 2.6 meters vertical error at 95 percentile and 2.0 meters horizontal error at 95 percentile. They also show temporal stability over a period of 40 days, as the station locations were determined on 25 October 1995.

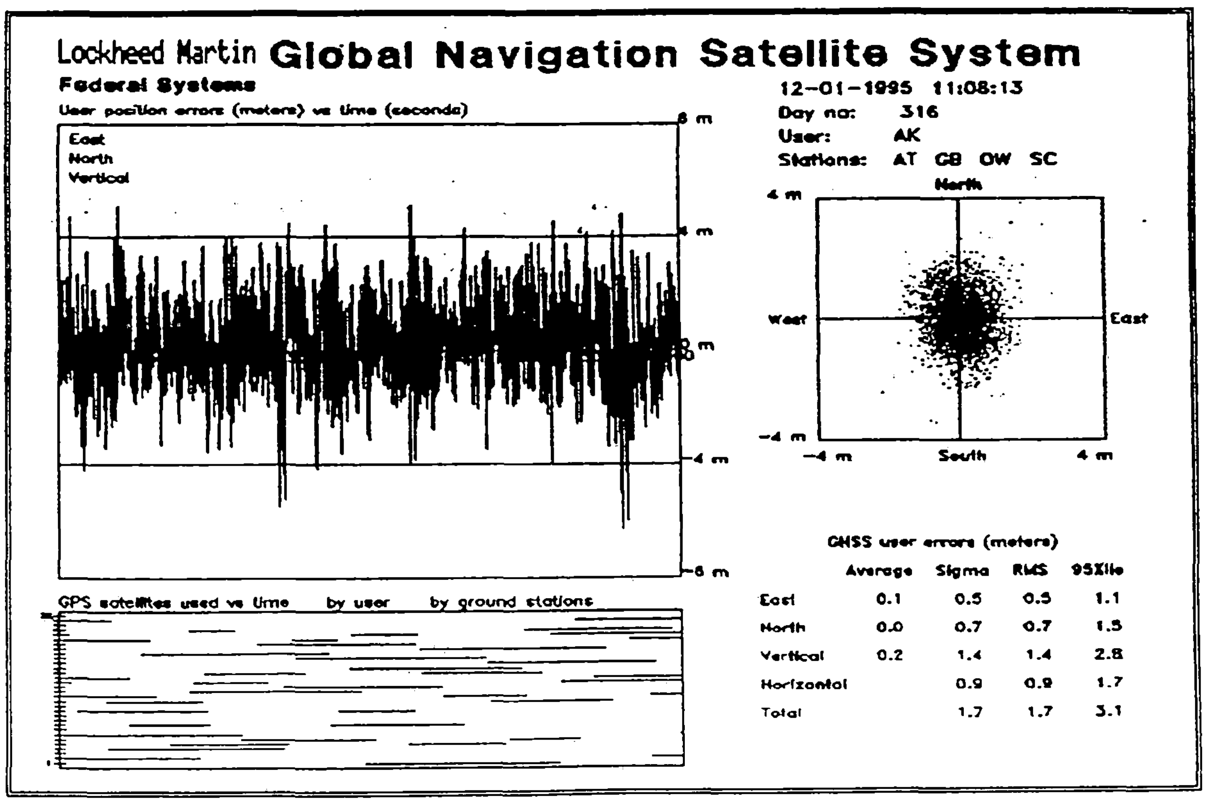


Figure 8 - Data from Full 24-Hour Test [Note: The figure is a composite of 4 plots: Vertical error, shown at upper left, Satellites used shown at lower left, Horizontal error scatter at upper right, and statistics.]

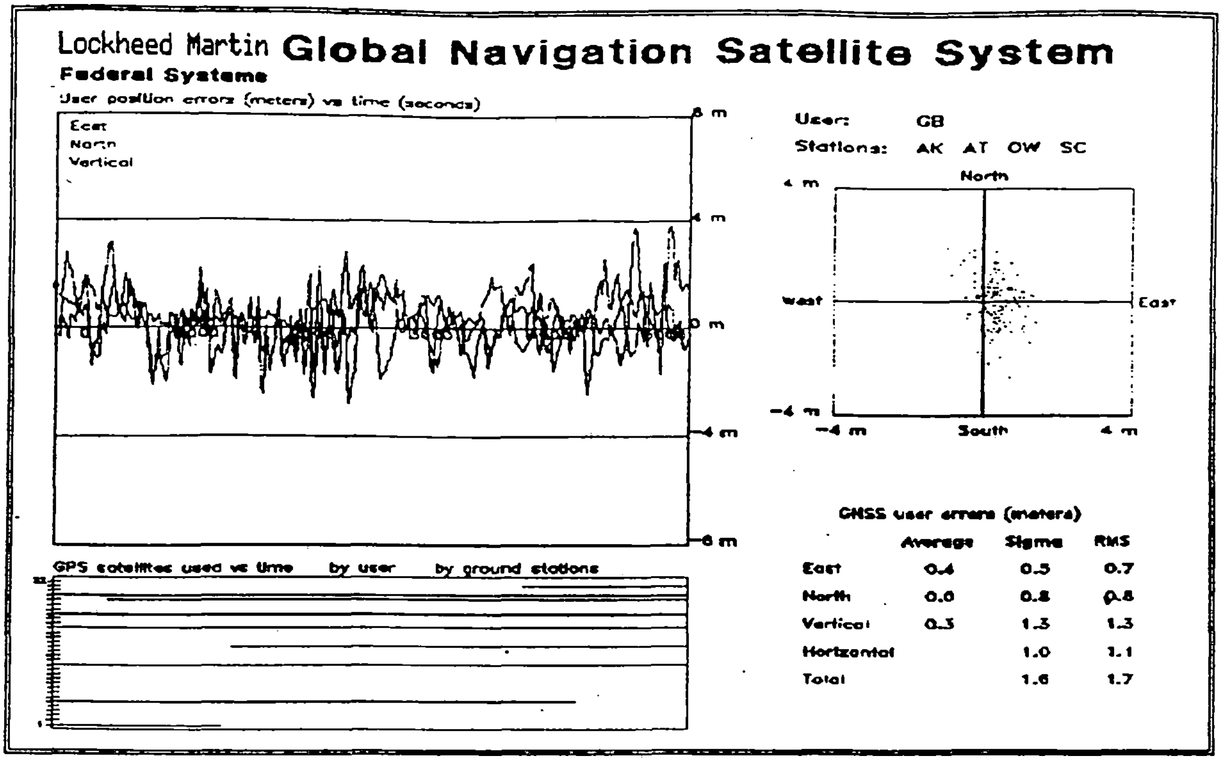


Figure 9 - Gaithersburg Antenna Movement Test Results [Note: The figure is a composite of 4 plots; Vertical error, shown at upper left, Satellites used shown at lower left, Horizontal error scatter at upper right, and statistics.]

Spatial and Temporal Stability

Another test of both spatial and temporal consistency was accomplished by processing 26 November 1995 data with each of five stations taken, in turn, as the user. The results for each of the five possible user station selections are shown in Table 3. The isolated station, then, simulates a user which may be several hundred miles from the nearest GNSS WADGPS monitor station. An 8 second latency was used.

Table 3 - Accuracy of Various User Locations

User Location	Vertical Error (meters) @ 95%
Akron, OH	2.0
Atlanta, GA	3.4
Gaithersburg, MD	3.1
Owego, NY	2.7
Scranton, PA	2.5
Average	2.7

The average vertical error is 2.7 meters at 95 percentile. The vertical error for each location is less than half the WAAS requirement of 7.6 meters. These results also show temporal stability, the station locations were established 32 days before.

Real Time System

The results shown above were obtained from the processing of recorded C/A code observations. The efficacy of the GNSS wide area differential GPS prototype was further proven by means of a real-time demonstration on 3 January 1996 for the FAA. A copy of the live screen is shown in Figure 10. This half hour of data, for Gaithersburg as the user, was typical of the demonstration which lasted several hours. The system is now routinely demonstrated with comparable results. The corrections are predicted 8 seconds ahead of the data.

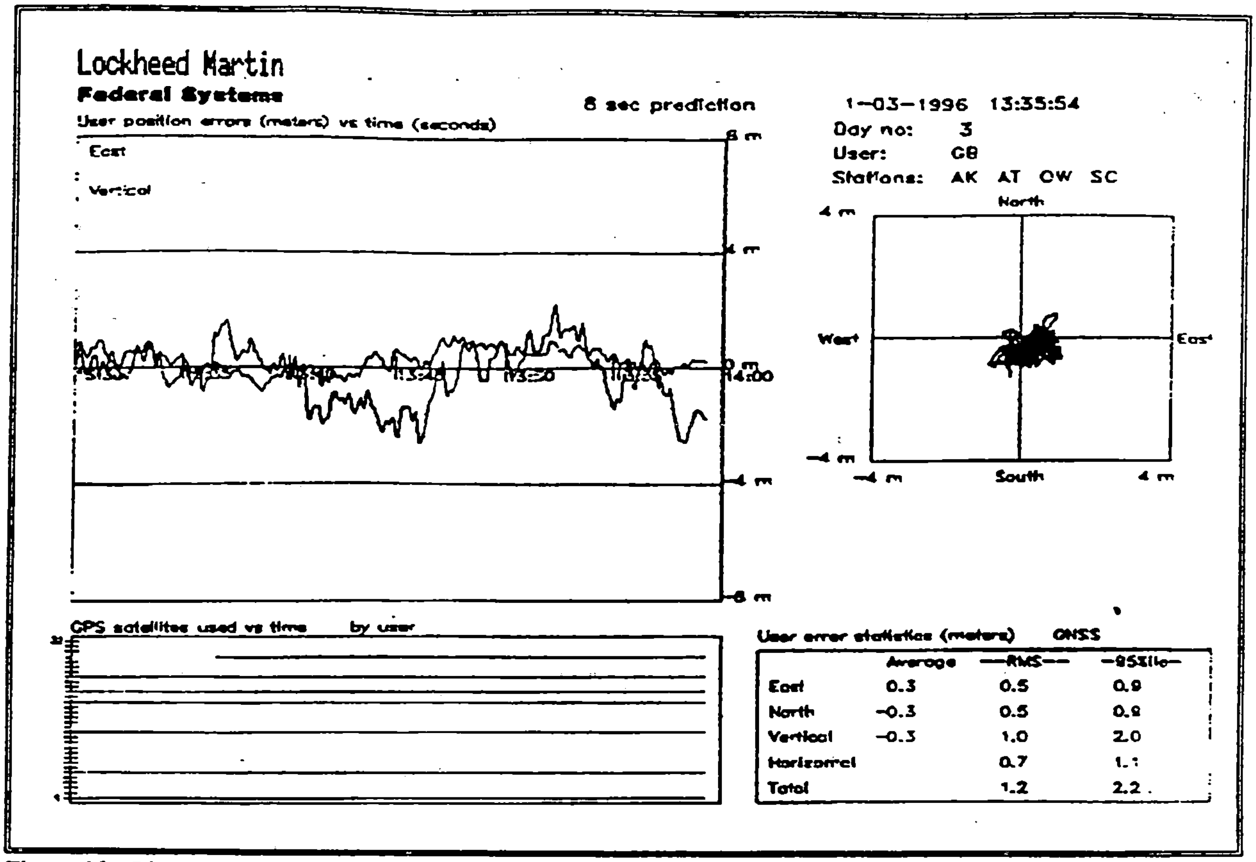


Figure 10 - Live Results During Demonstration [Note: The figure is a composite of 4 plots; Vertical error, shown at upper left, Satellites used shown at lower left, Horizontal error scatter at upper right, and statistics.]

Results with P-code

In addition to the C/A code outputs, the Ashtech Z-12 also offers P1 and P2 ouputs. We have performed limited testing with these data streams, however, the results have been surprisingly good. When P1 or P2 were used for both the Monitor Sites and the user receivers, the accuracy of the testbed improved markedly.

Figure 11 shows a 24 hour run using the P1 outputs from all receivers. The horizontal error has improved to 0.8 meters 95% and the vertical error has improved to 1.2 meters 95%. All of the measurements for this run meet the accuracy requirements for Category II precision approaches. (There is no implication here that this system will meet the Category II precision approach requirements for availability, continuity or integrity).

There is also a noticeable bias in the East and Vertical components of -0.3 and -0.2 meters respectively. The size of this bias is a concern and will need to be evaluated in future work.

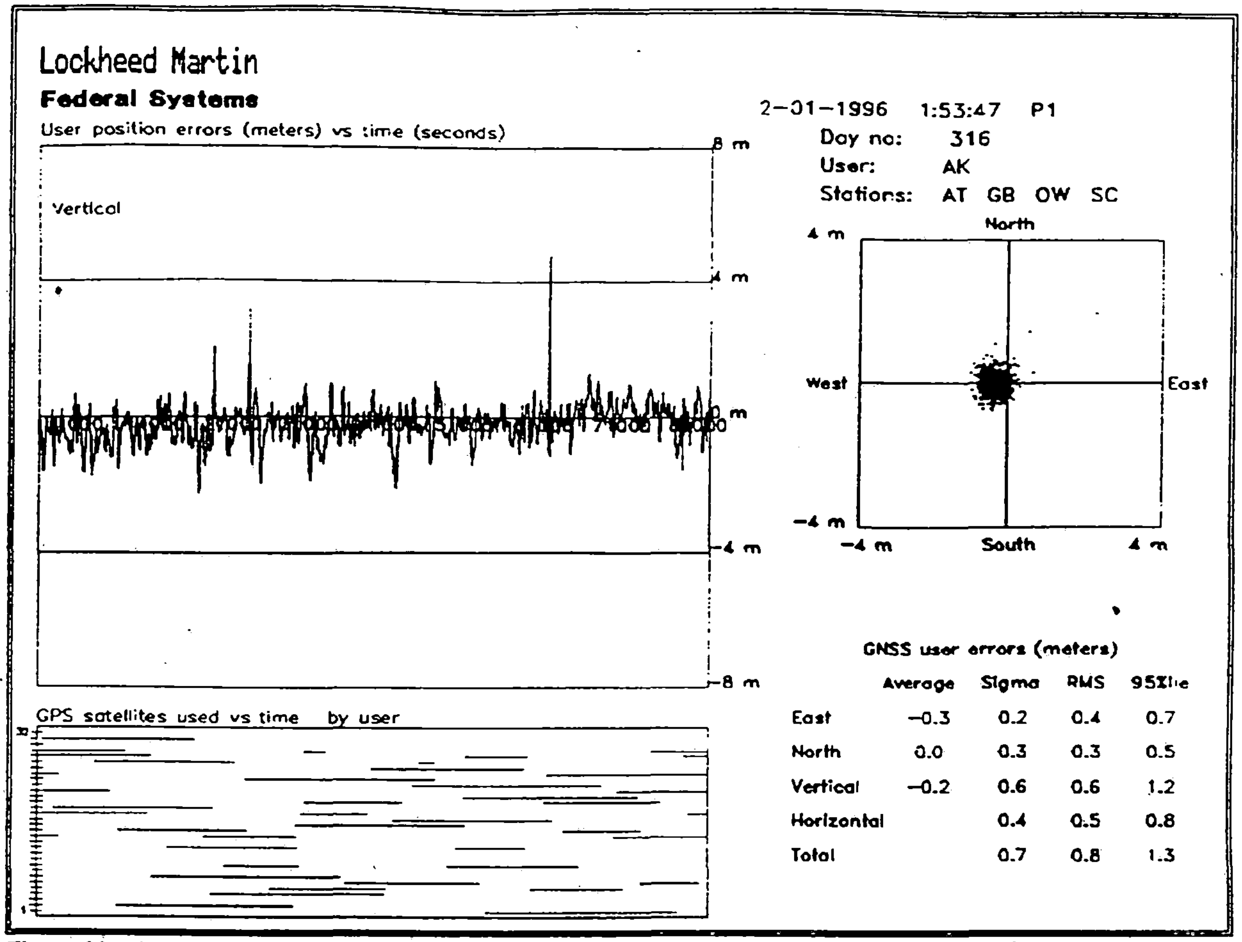


Figure 11 - Accuracy Results Using Ashtech P-Code Inputs Note: The figure is a composite of 4 plots; Vertical error, shown at upper left, Satellites used shown at lower left, Horizontal error scatter at upper right, and statistics.]

Extension to Operational System

The LMFS wide area differential GNSS testbed is both a useful analysis tool and a valuable prototype for the core of an operational system. It contains the majority of algorithms needed for a wide area differential system for GPS alone or a GNSS. This existing capability translates directly into a lower risk design and production phase. The algorithms have already been tested and any proposed algorithmic changes can be verified on the testbed with much higher confidence than analysis alone would provide. The existence of tested algorithms will also allow a faster production schedule, with less time needed for the engineering design phase of the program. While there is the possibility of software reuse, the majority of the software in the operational system will have to be written and tested according to RTCA/DO-178B [2] or an equivalent safety critical software specification. During the testing phase, the testbed can be used as a means of validation, as a comparison source, and as a test source for algorithmic improvements.

Conclusions

The LMFS wide area differential GNSS testbed is being demonstrated routinely to yield accuracies more than twice those required by WAAS. Using C/A code, vertical errors are consistently less than 3 meters, at 95 percentile, which is less than half the 7.6 meters specified by WAAS. Similarly, the horizontal errors are 2 meters or less 95 percentile. Further, this accuracy is being obtained using only crystal clocks in the MS. Using P code, the errors meet the Category II precision approach accuracy requirements.

These accurate results are important, not only for attaining user navigation objectives but for improving the availability, continuity and integrity of the system. The better the accuracy of a system, the more margin that is available for performing integrity checks. The larger margin will result in decreases in both the probability of Hazardously Misleading Information and the probability of false alarms. Thus a more accurate system increases availability, continuity and integrity and contributes significantly to the overall level of safety provided by the system.

Acknowledgements

The authors would like to thank Robert Benner, Gabe Chang, Mark Greenlee and Todd Phelps of LMFS-Gaithersburg for their dedication and ingenuity in making the testbed a success.

For their contributions to the design, system architecture and the algorithms the authors thank Ming Chien, Dwight Divine III, Sherm Francisco, Dan Frederick, Peter Hoch, Chuck Kengla, Mike Patrick, and Dick Taylor of LMFS-Gaithersburg

Thanks to Karl Kovach of Arinc Research for his support and helpful suggestions.

In addition, we would like to thank our MS teams of Jim Wildenstein, Lisa Garrick, and Dan Lostoski of Lockheed Martin Tactical Defense Systems; Ken Flanagan, Christy Van Winkle and Jackie Huff of Lockheed Martin Display Systems; and Ravi Shah and Ed Kenyon of LMFS - Owego.

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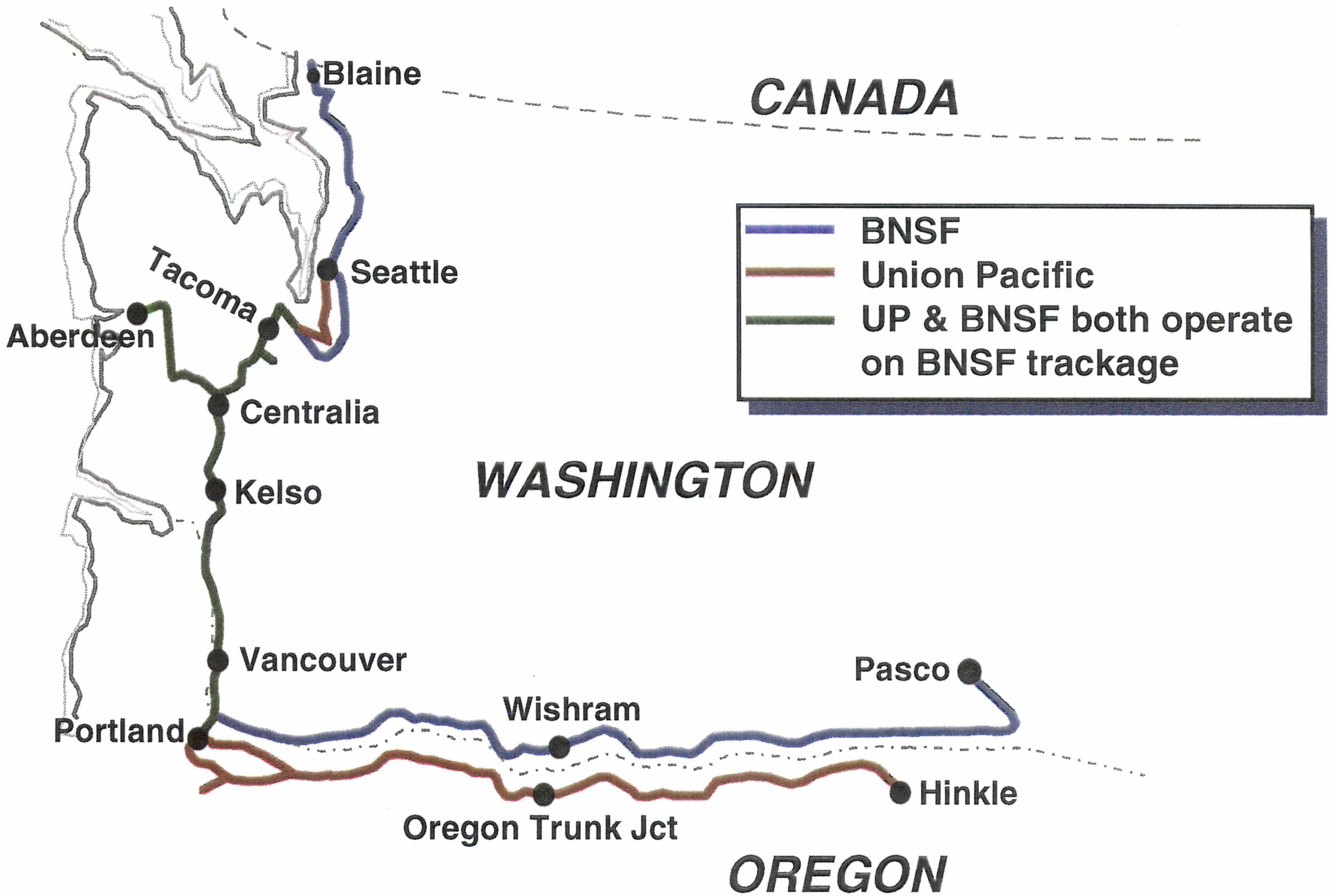
GE HARRIS
Railway Electronics

Pacific Northwest Positive Train Separation System

fjm110496-447

PTS Pilot Region



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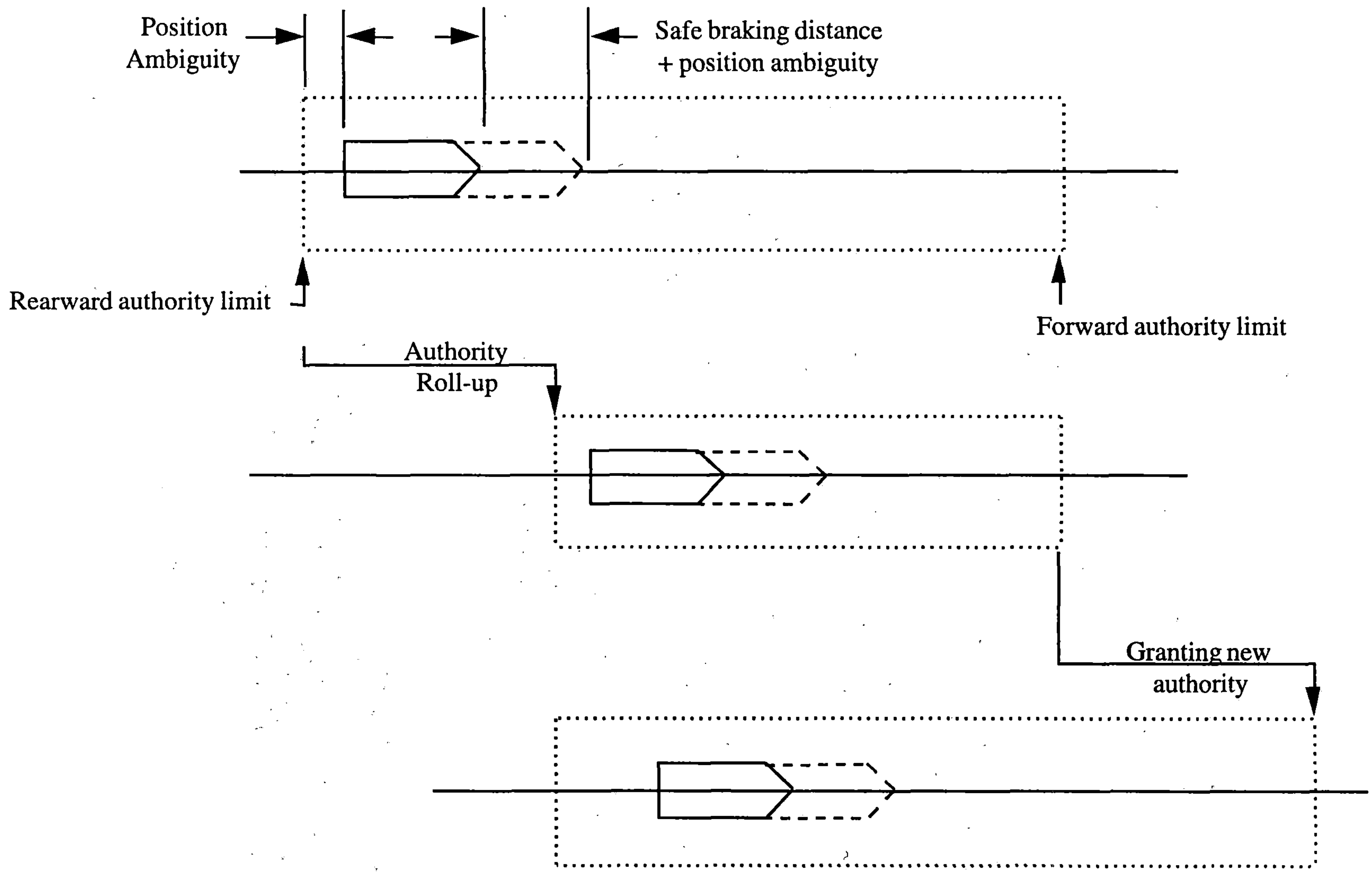
Basic Safety Monitor Operation



Location Determination is Critical to PTS Operation

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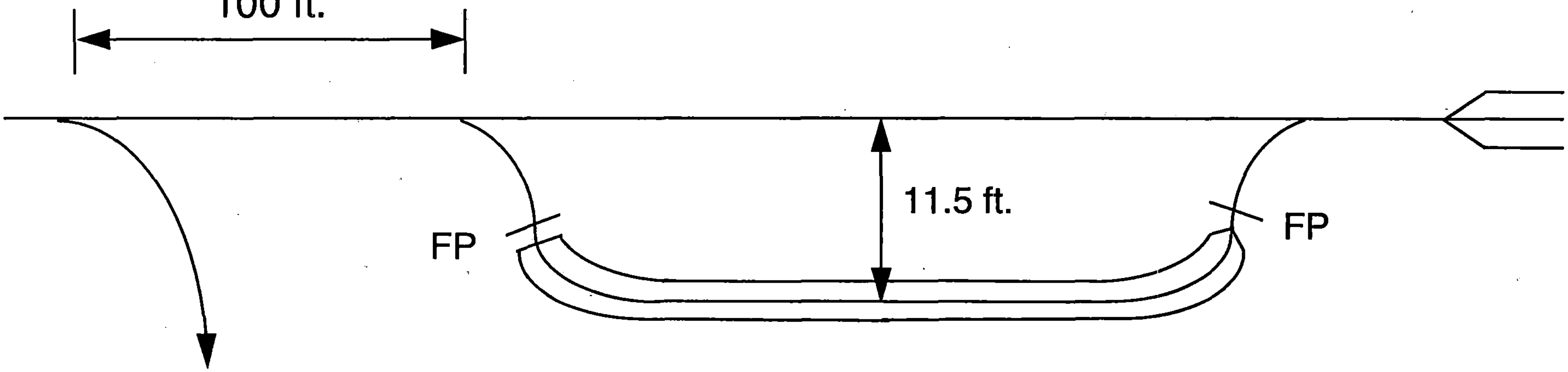
Basis of Location Determination Requirements



LDS Must Resolve Parallel Tracks and Linear Position On Track

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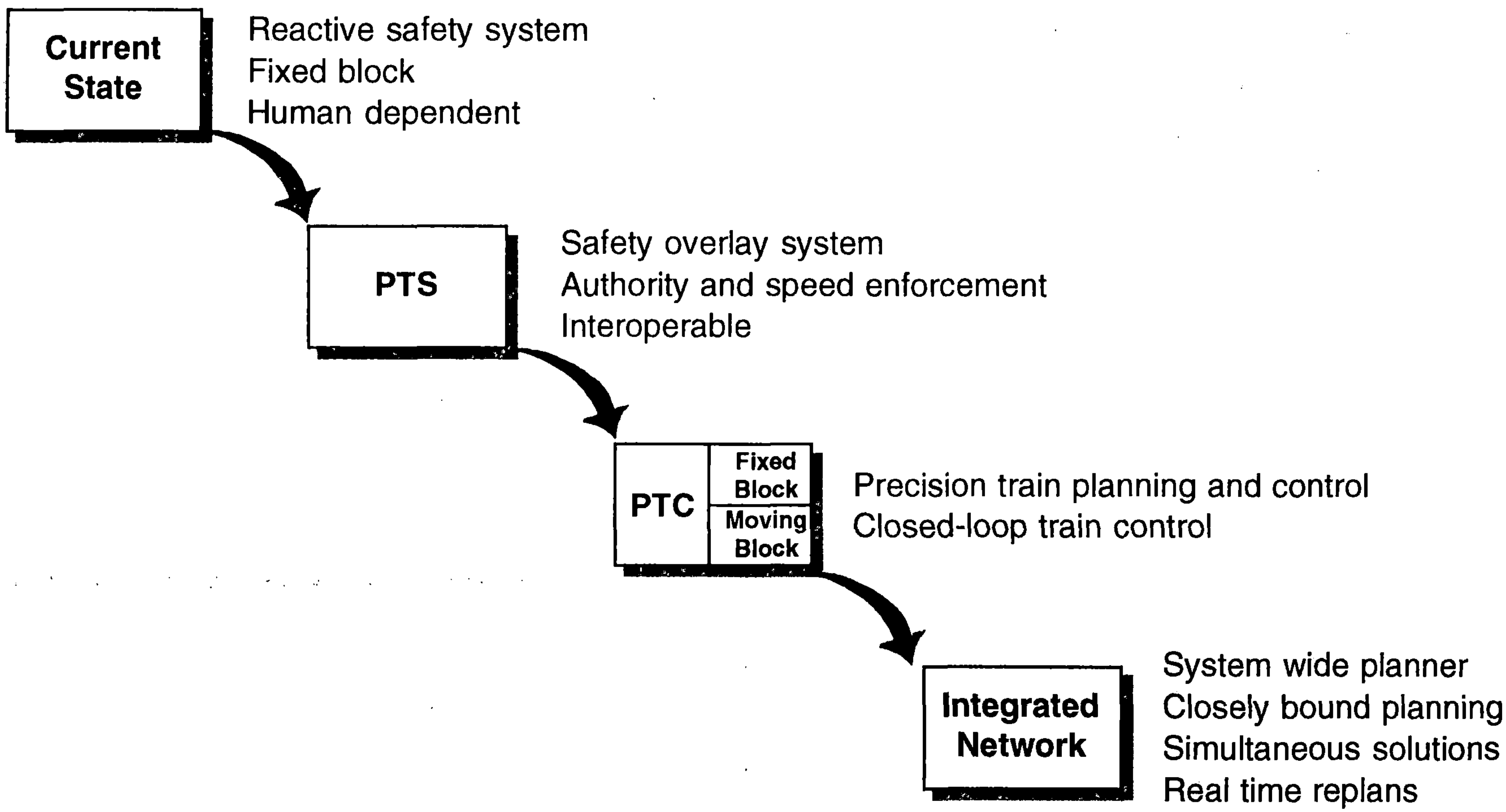
System Evolution



MultiGenerational Functional Growth

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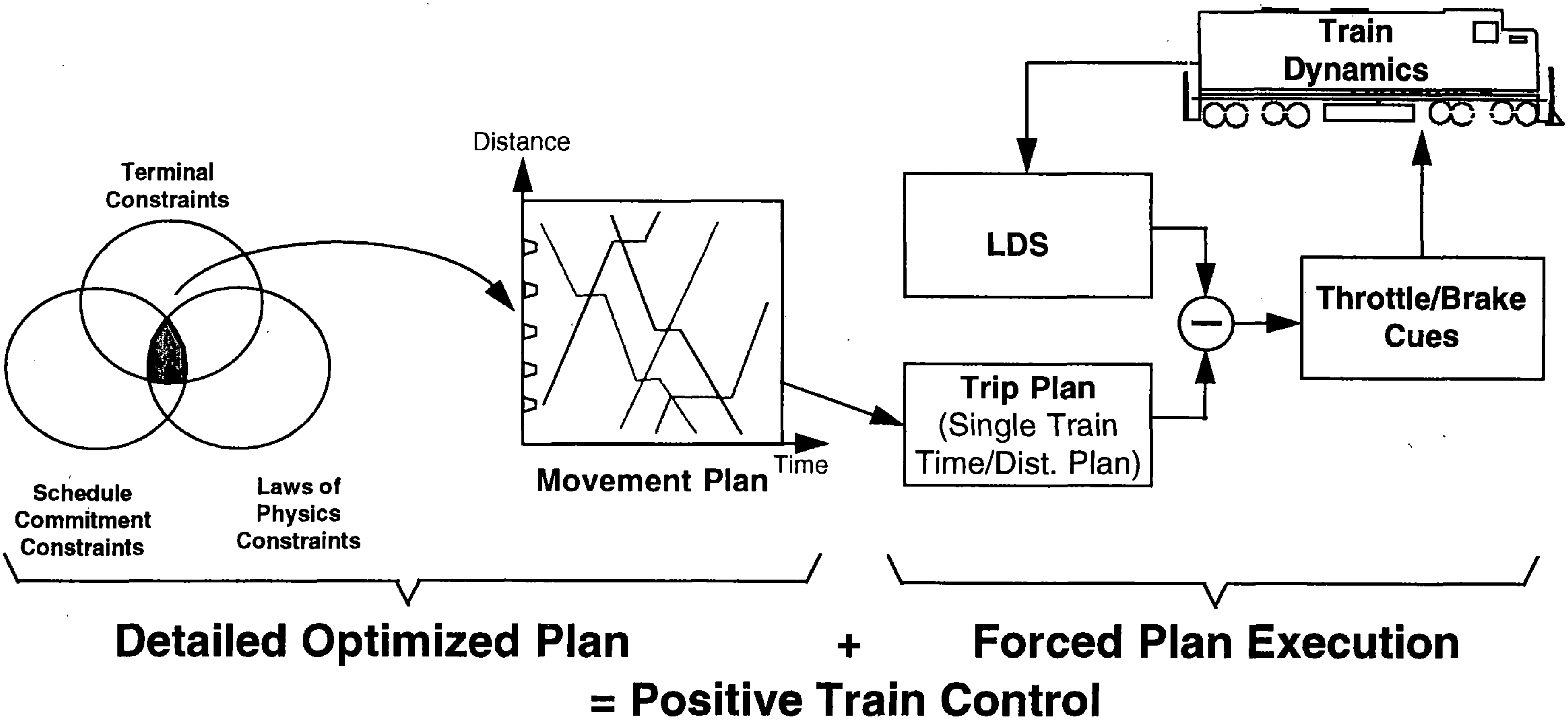
How Does Positive Train Control Work?



PTC Binds Execution to an Optimized Plan, Resulting In:

- **Less Time Wasted by Trains Waiting for Meets and Passes**
- **Efficient Merges Through Train Pacing**
- **Less Congestion Via Flow Control**
- **Less Domino Effect From Anomalies**

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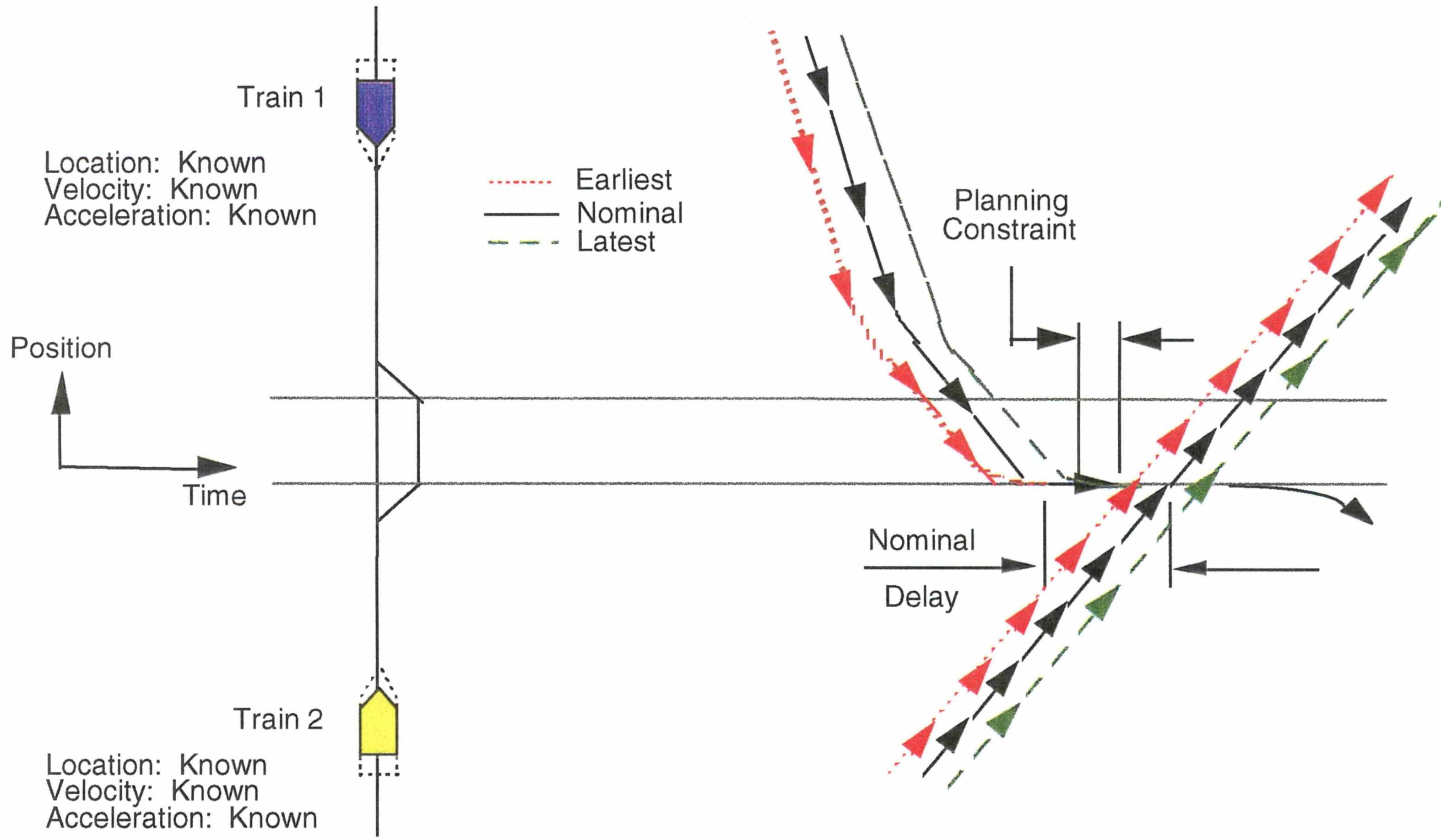
PTC Meet Scenario



Precision Tracking and Control Improve Operational Efficiency

fjm110496-447

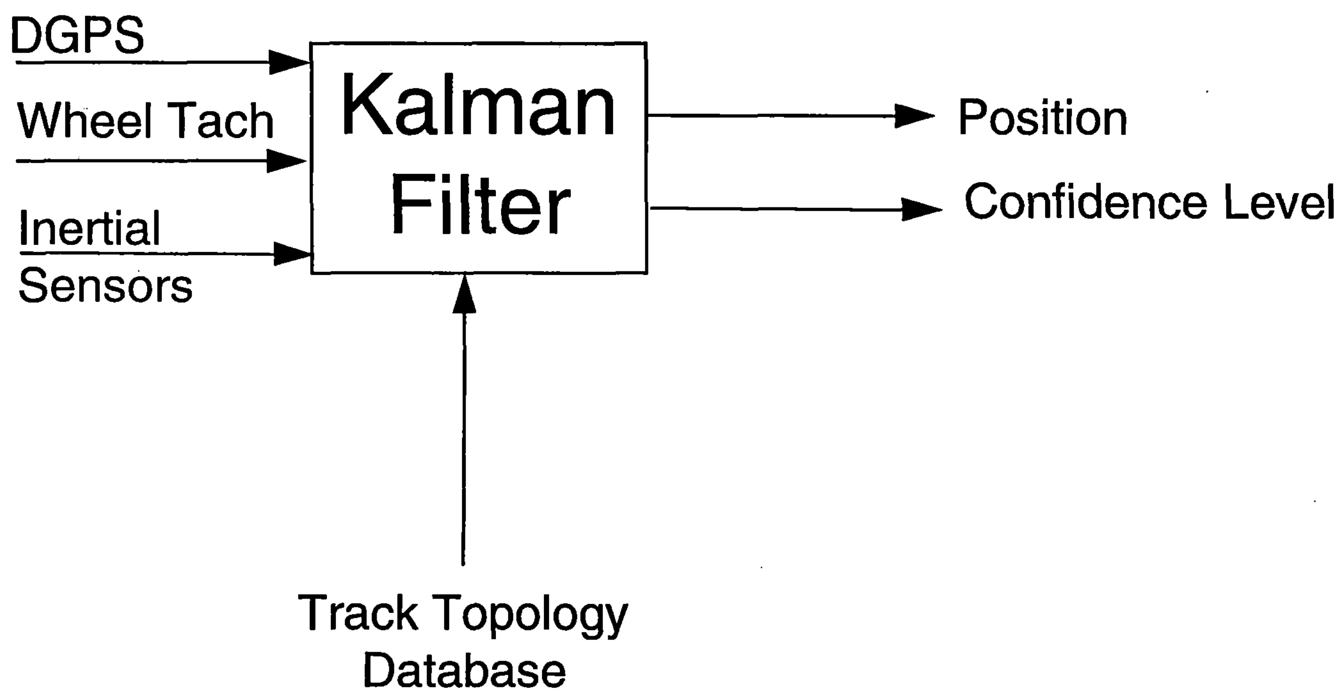
Quantative LDS Requirements

1. Resolve Parallel Tracks 11.5 Feet Apart to 0.99999 Assurance.
2. Resolve Line or Position at *Critical Points* to $\pm$ 50 Feet With 0.99999 Assurance.
3. Allow Short Term Outages of Any One Sensor.

Requirement Can Not Be Satisfied With Any Single Sensor

fjm110496-447

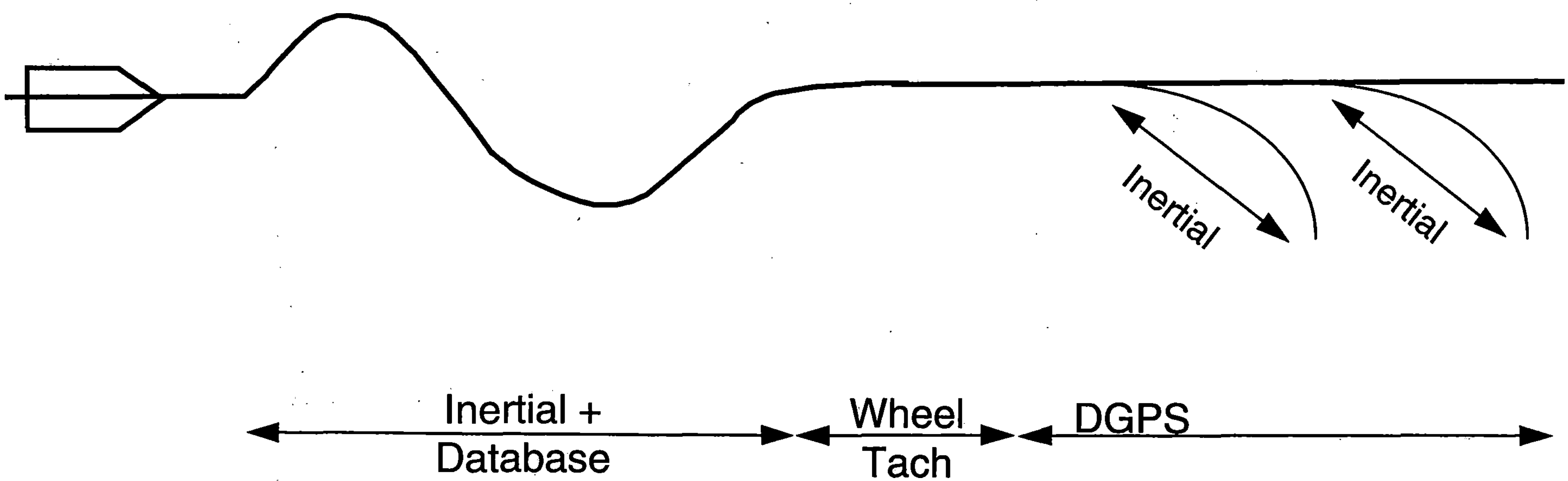
LDS Architecture



LDS Provides Greater Accuracy and Robustness
Than Any One Sensor Can Provide

fjm110496-447

Role of DGPS



DGPS Is Critical To Resolving Control Points On Tangent Track

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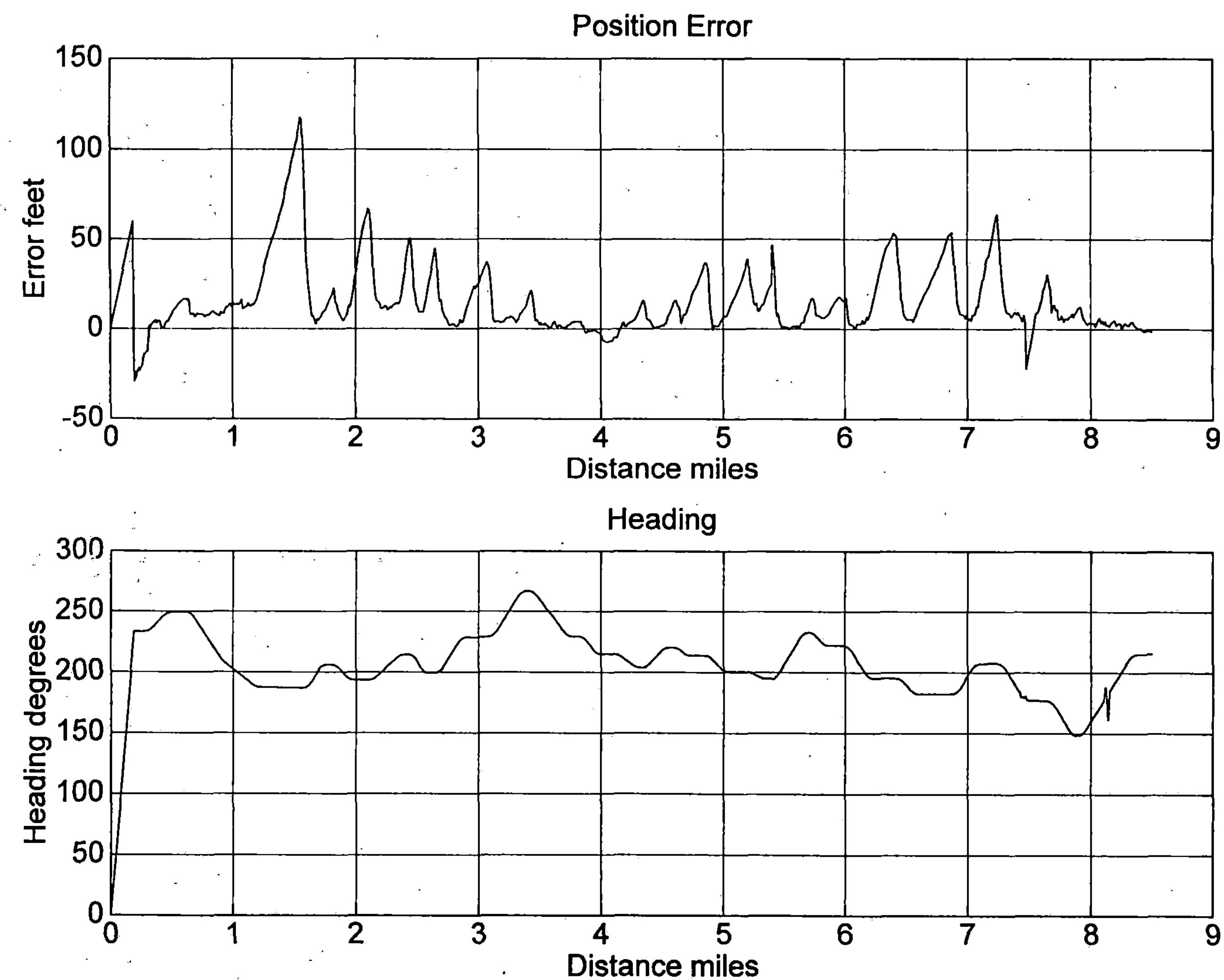
Position Error With Wheel Slip Without DGPS



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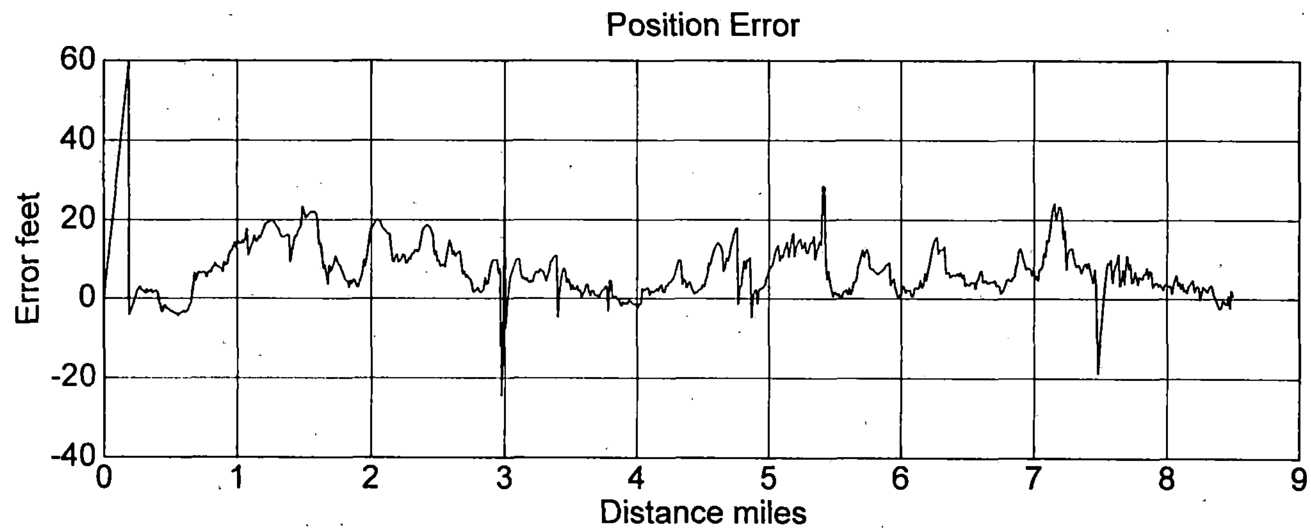
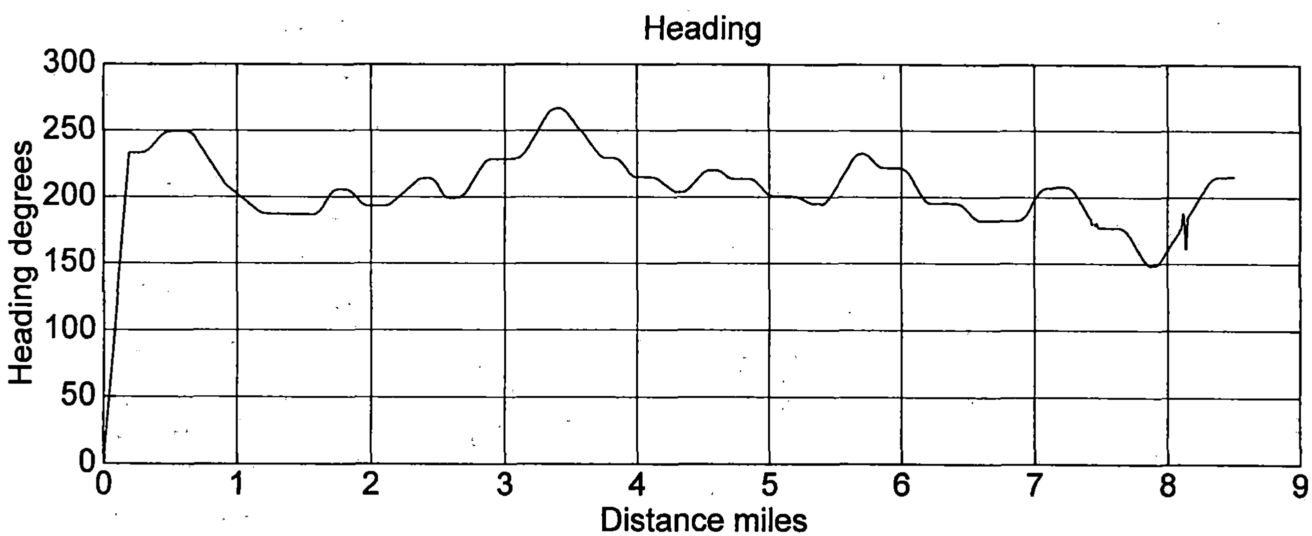
Position Error With Wheel Slip Using DGPS





fjm110496-447

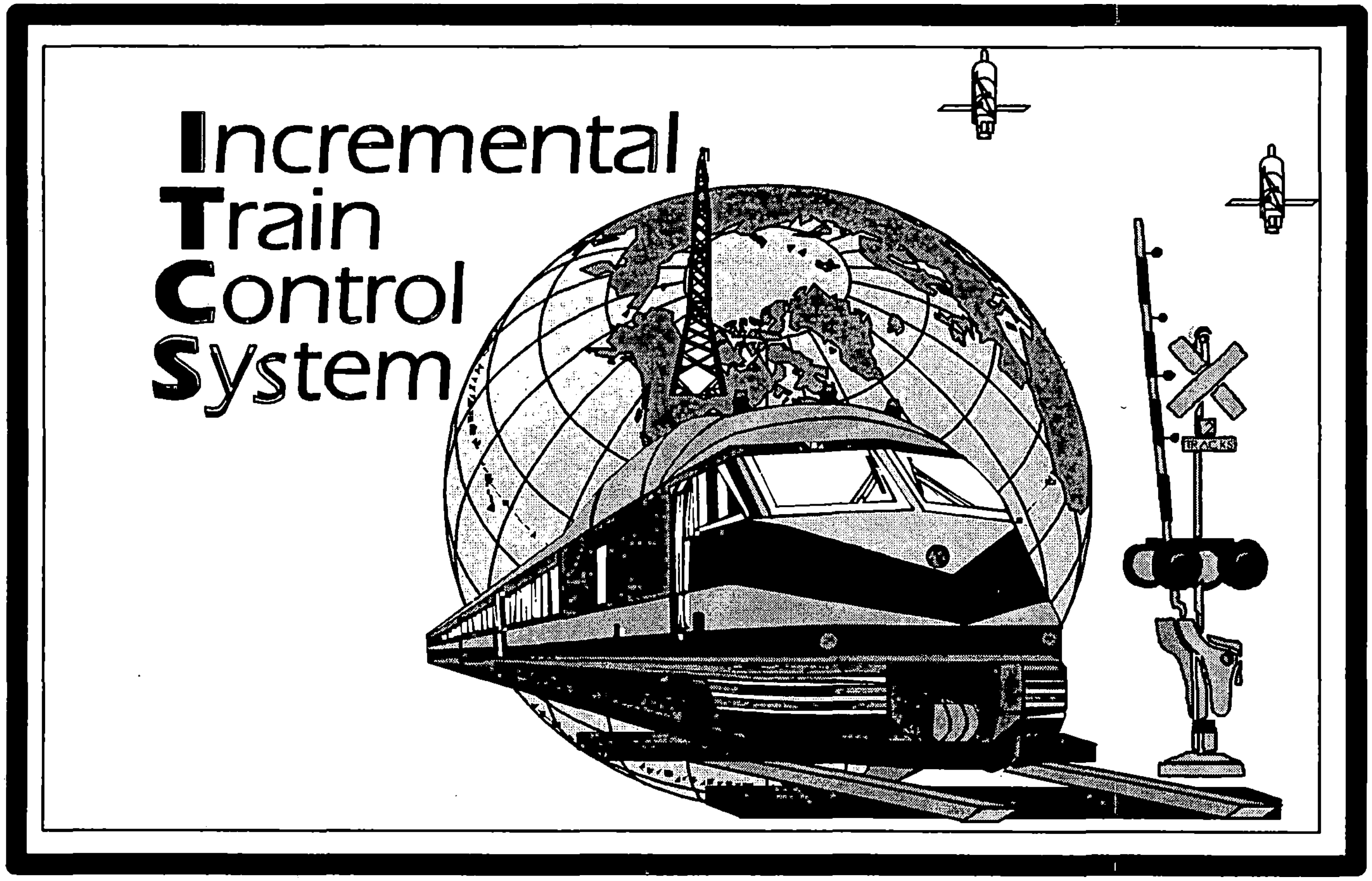
Summary

To efficiently support the advances in Railroad Productivity and Safety Improvements, a DGPS service is needed which provides:

1. *Nation-wide Coverage*
2. *Assured Availability*
3. *Assured Integrity*

GPS For ITCS

Harmon



GPS for ITCS

Harmon

presented by

Don Schaefer
Manager, Advanced System Development
Harmon Industries

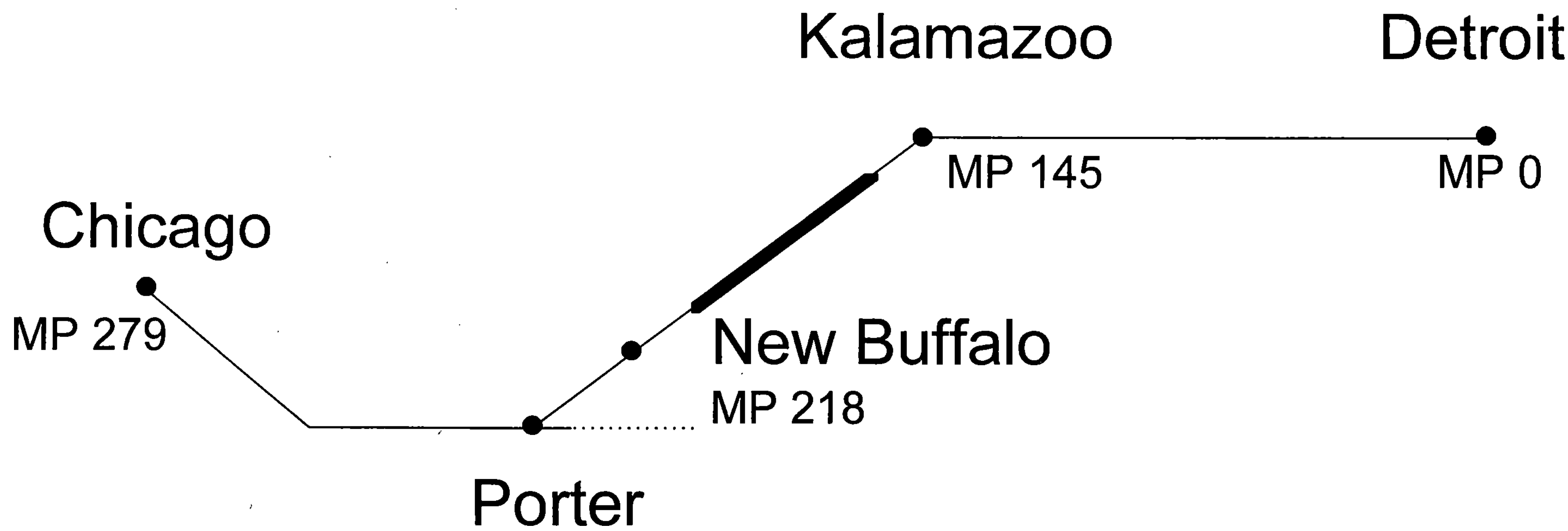
Steve Bauer
Senior Systems Engineer
Harmon Industries

Topics

Harmon

- Overview of ITCS
- GPS Uses in ITCS
- GPS Accuracy

ITCS HS/PTS Michigan DOT



ITCS Features

Harmon

- Enforcement of Track Speed Limits
- Enforcement of Signal Aspects
- Enforcement of Temporary Speed Restrictions
- Support of High Speed Operation
  - Advance Start of Crossings
  - Feedback of Crossing Status

ITCS - System Issues

Harmon

- Primary Information Source is Distributed Vital Logic
- Primary Decision Making is On-Board
- Train-Wayside Communication
  - MCP Out of Coverage Mode
  - No synchronization links
- Location Determination
  - Differential GPS
  - Axle Tachometers
  - Switch Position

GPS Uses in ITCS

Harmon

- Real Time Location Determination
- Synchronization Of TWC Network
- Track Survey

GPS Track Survey

Harmon

- Used to Create Track Databases
  - Used In The Onboard Computer
  - Track Map Contains The Horizontal Alignment
  - Track Profile Contains The Points Of Interest And Grade
- Each Survey Point
  - Point of Interest or One Tenth Mile Interval
  - Five Minutes Per Point (average)

GPS Survey Technique

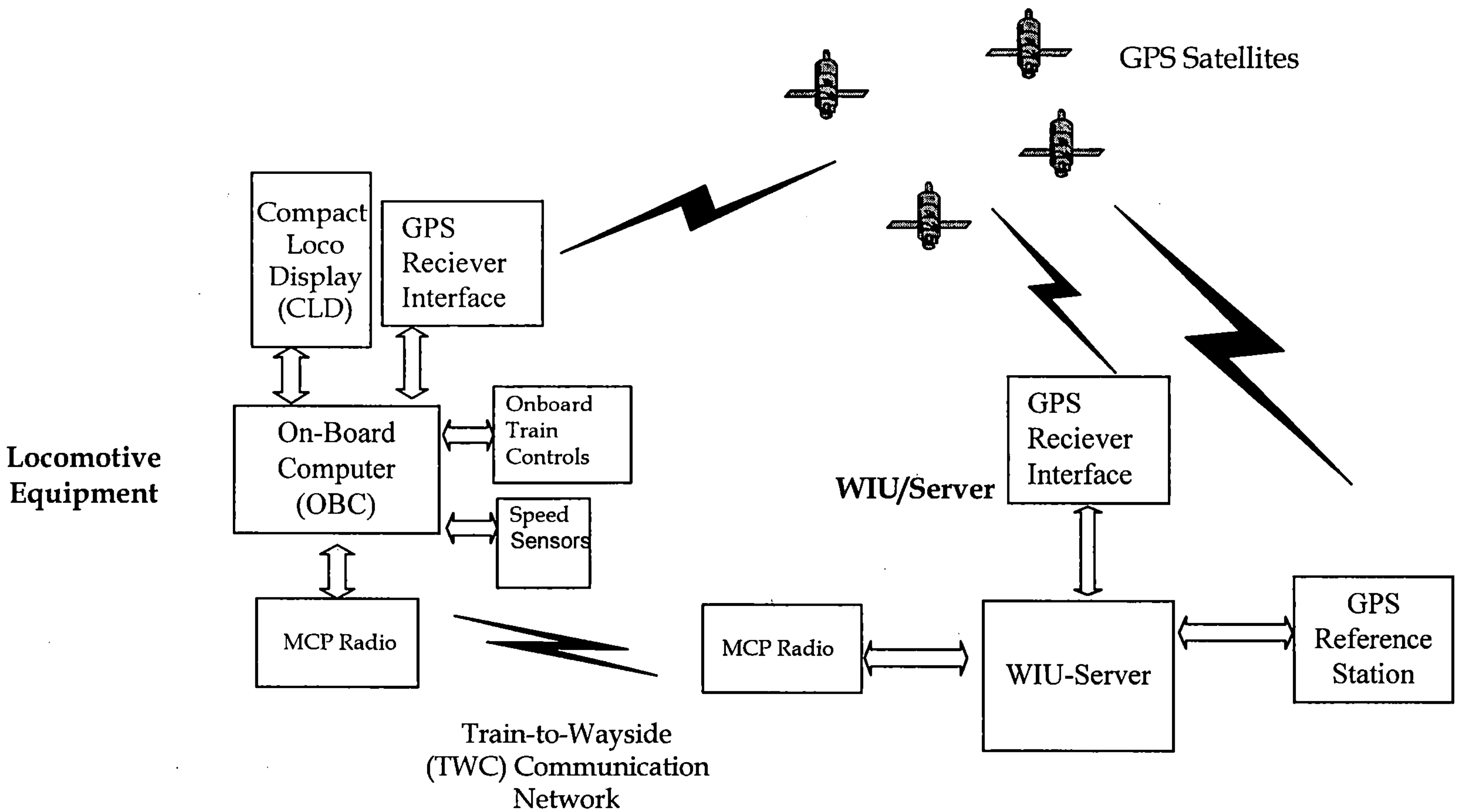
- Real Time Kinematic Method
  - Dual Frequency Receivers
  - Carrier Phase Measurements
  - Corrections Broadcast From Nearby Base Stations
- Data Point Accuracy 0.5 Feet (Worst Case)
- Database Accuracy 1.5 Feet (Worst Case)

Synchronization of TWC Network

Harmon

- GPS Receivers Provide Time Accurate to a Fraction of a Microsecond
- GPS Time is Transferred to Each MCP Radio
- Each Radio Transmits Only During Its Assigned Slot
- RF Collisions Are Reduced

ITCS Block Diagram



Onboard Location Determination

- Differential GPS Position From a Motorola Receiver
- Position Compared to Track Map Database
  - Converted to Components
    - Location Along the Track
    - Off Track Distance (Perpendicular to the Track)
  - Location Rejected If Too Far off Track
- Location Used As a Measurement in the Location Filter

Location Filter Features

Harmon

- Computes the Final Train Location
- Consists of a Software Kalman Filter
- Propagates Locations Between GPS Measurements
- Rejects GPS Locations That Are Too Far From the Propagated Location
- Improves Location Accuracy

Location Filter Measurements

Harmon

- Measurement Types
  - GPS Location
  - GPS Velocity
  - Axle Tachometer Velocity
- Measurements Weighted According to Their Modeled Accuracy
- Measurements Compared to Predictions Made From the Propagated State
- Bad Measurements Are Rejected

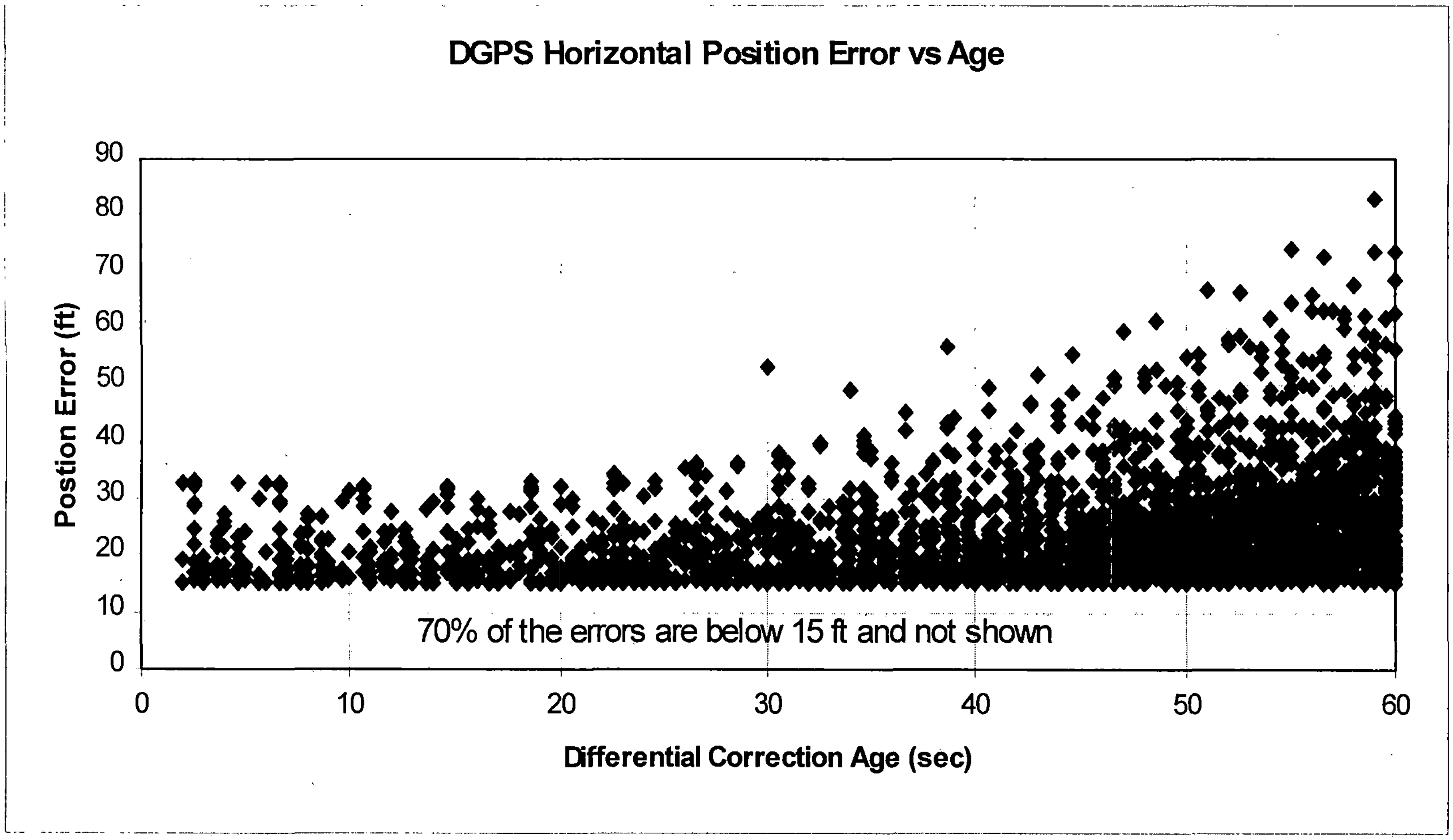
Differential Correction Technique

Harmon

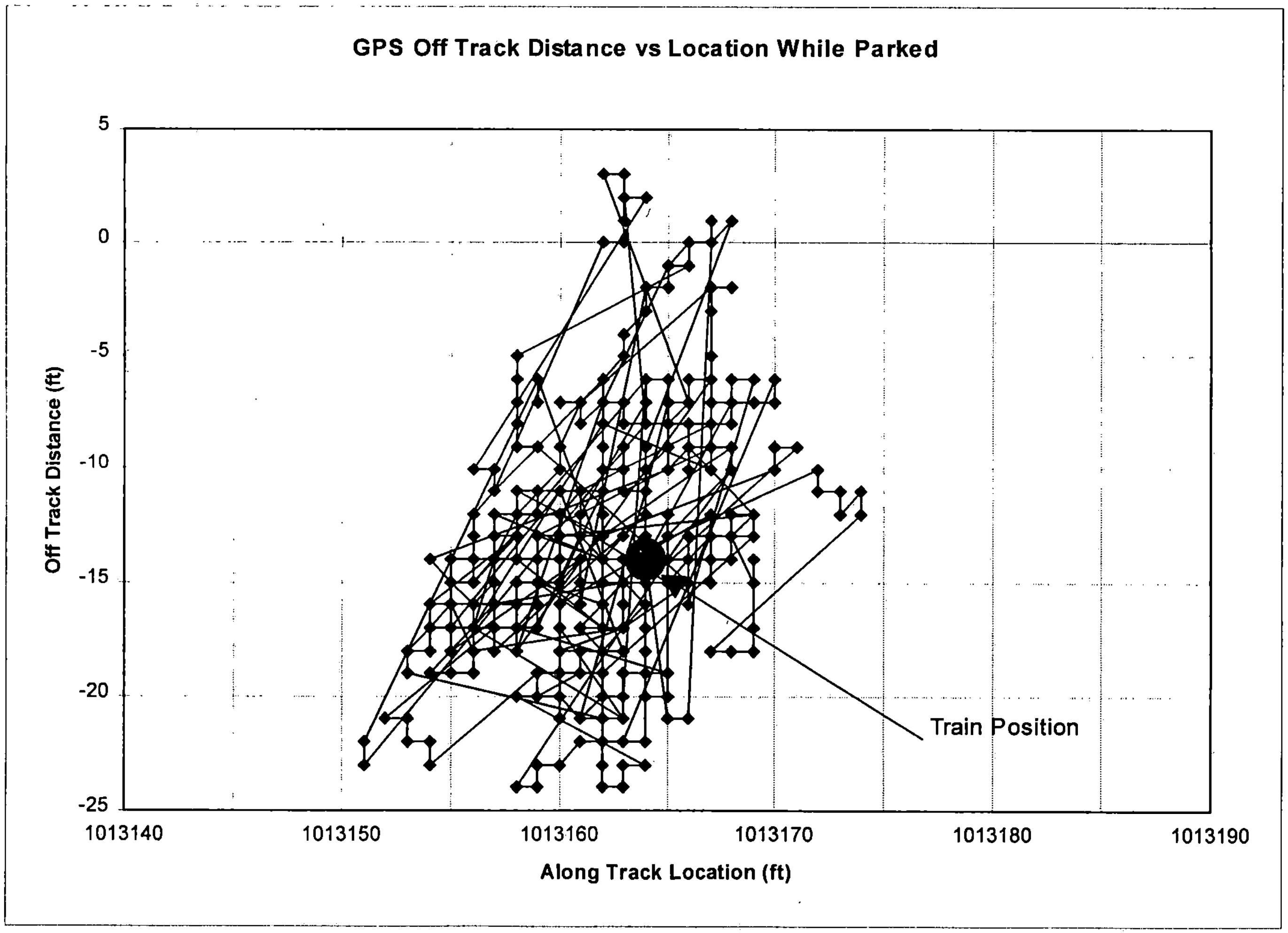
- Reference Stations Located at Each Server
- Corrections Broadcast Over the TWC Network
- Corrections Also Sent to Monitor Receiver
  - Located at the Server
  - Server Compares Computed Position to Known Position
  - Warns Trains When Errors Are Large

DGPS Accuracy

Harmon

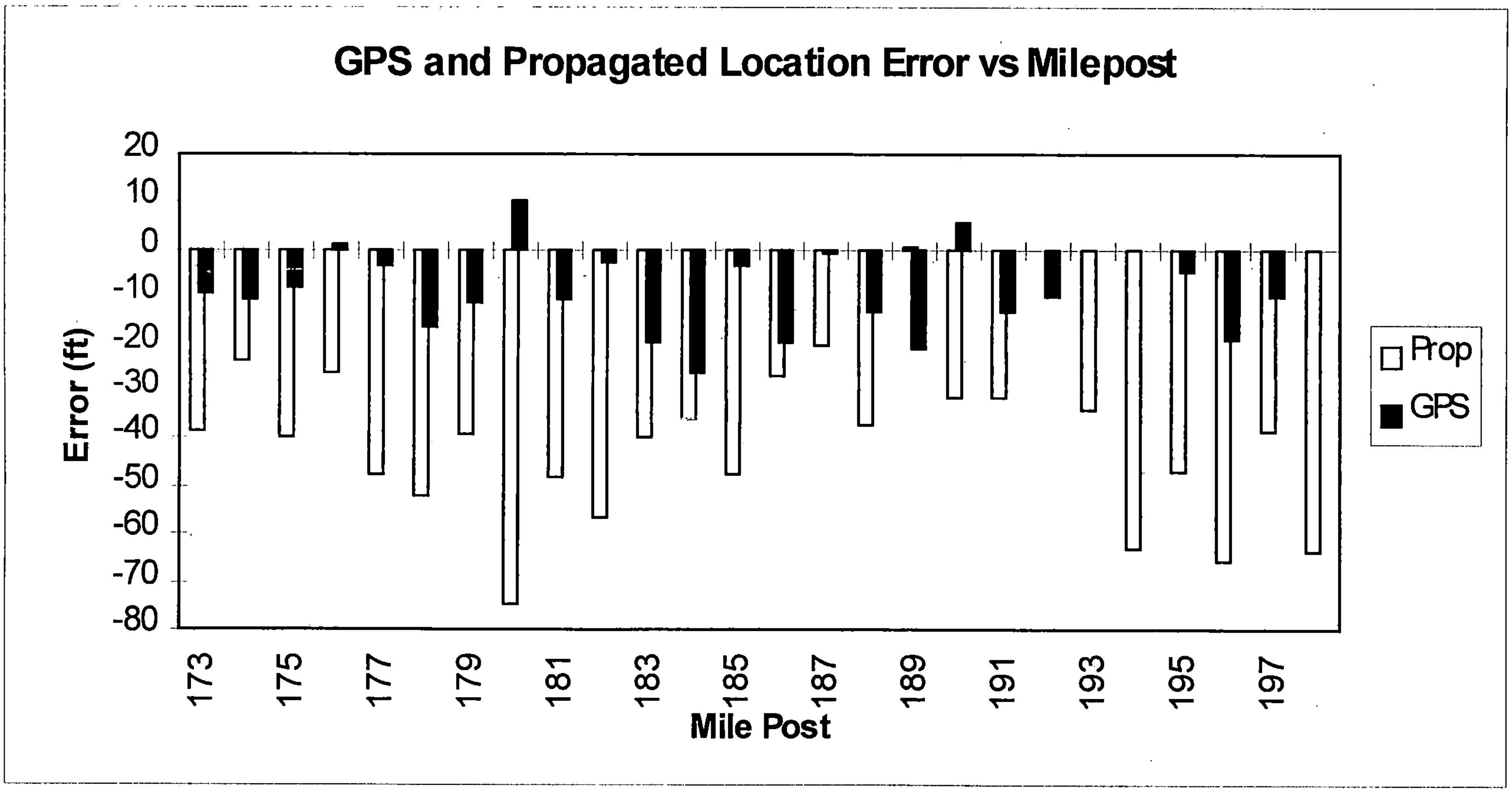


Onboard GPS Wander

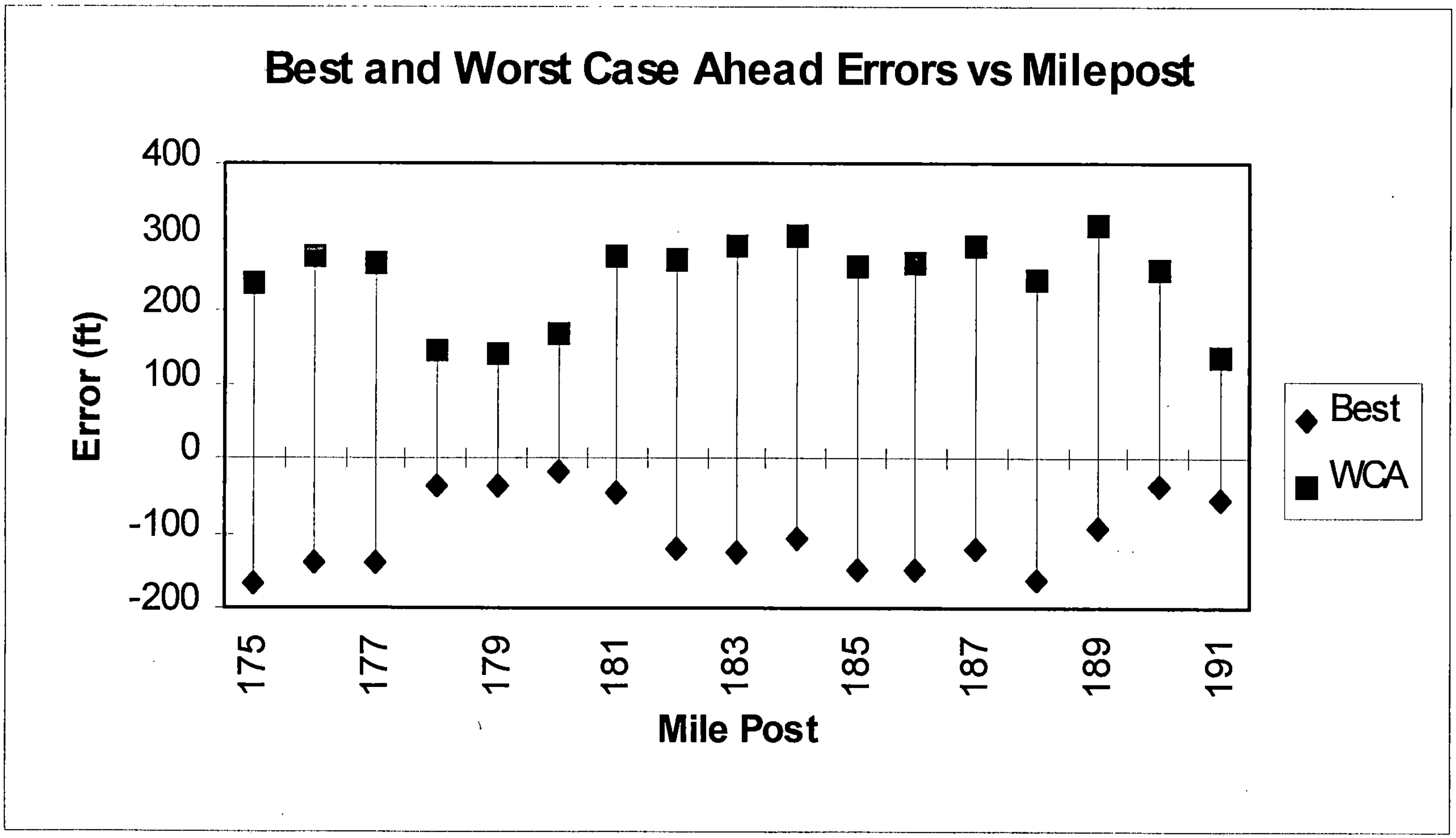


Location Errors At Stops

Harmon

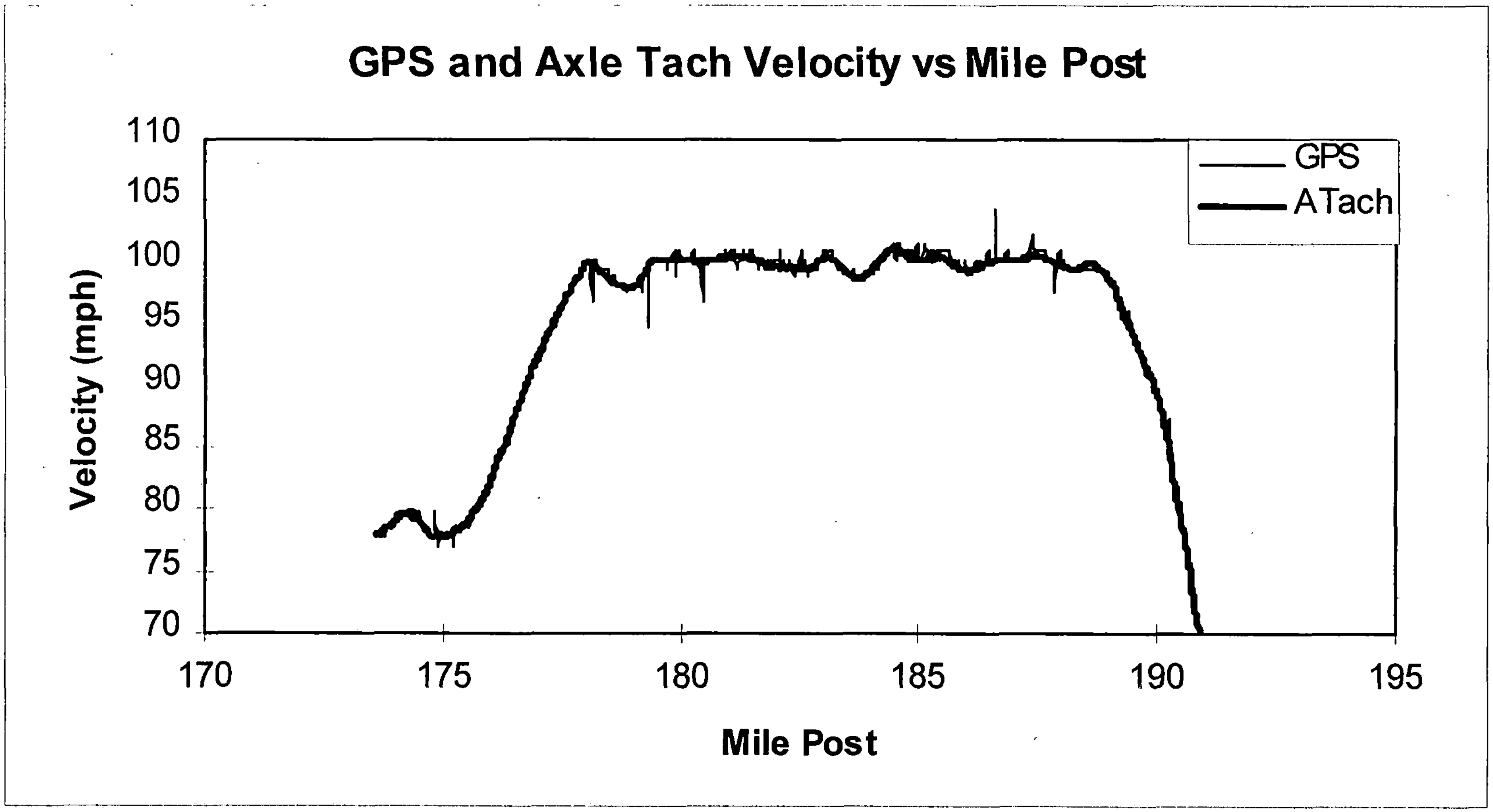


Location Errors While Cruising

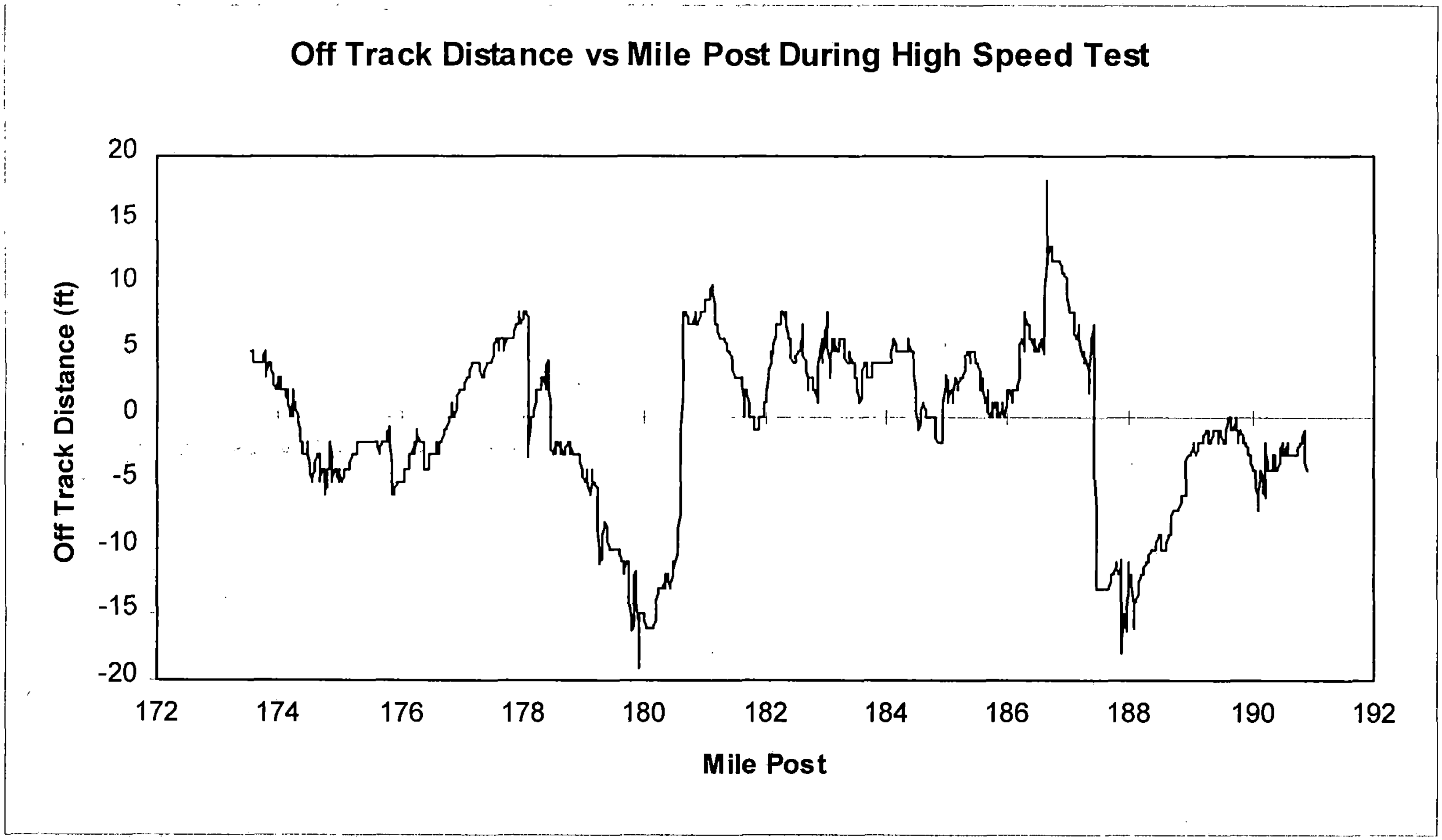


Velocity Comparisons

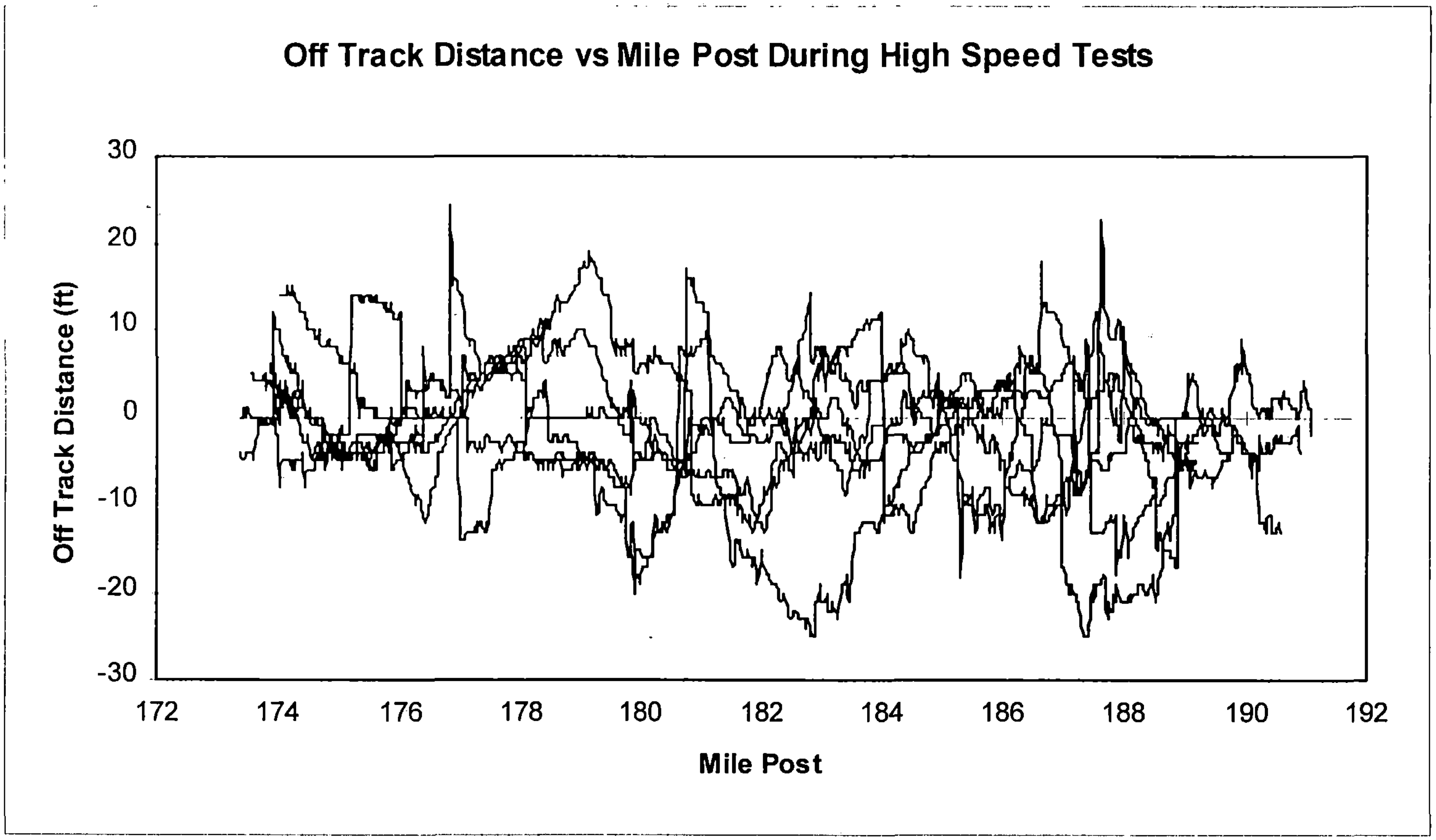
Harmon



Off Track Errors (1 Trip)



Off Track Errors (6 Trips)



Onboard Accuracy Summary

Harmon

- Accuracy Calculated As the Standard Deviation of Observed Errors
- 45 Hours of Tests While Parked
  - Along Track Accuracy = 6.1 Feet
  - Off Track Accuracy = 7.3 Feet
- 6 High Speed Runs
  - Off Track Accuracy = 6.9 Feet

GPS: Railroad and Other Transportation Applications

Agenda

- ❑ **Background**
- ❑ **GPS: The tool**
- ❑ **GPS: The benefits**
- ❑ **Land Transportation Applications**
  - Railroad Electronics
  - Transit Systems
  - Highway Transport Electronics
  - Automotive Electronics
- ❑ **Summary**

GPS: Railroad and Other Transportation Applications

Background

- **Global GPS leadership since 1974**
  - Initial GPS development team member
  - 100,000+ receivers sold to date
- **Pioneered railroad application of GPS**
  - Advanced Railroad Electronics System (1984)
    - Train control
    - Maintenance of Way control
    - Traffic planning
    - Asset management

GPS: Railroad and Other Transportation Applications

GPS: The tool

- **Precision of solution driven by application requirements**
  - Train control: higher precision, availability & updates
  - Asset management: lower precision, fewer updates
- **"Position" alone typically not enough**
  - Database requirements
    - Lat/Long v. Milepost or other reference point
    - On-board v. Off-board solutions
  - Communication infrastructure almost always required
    - Telling others where you are

GPS alone is merely a position input

GPS: Railroad and Other Transportation Applications

GPS: The benefits

- **Integrated position information provides measurable benefits to the customer:**
  - Improved efficiency
  - Improved productivity
  - Improved customer service
  - Improved information gathering
- **Two-way communications coupled with position reporting has been adopted by all major truck fleets in the U.S.**
- **All new Rockwell Railroad Electronics products are evaluated for value-added GPS benefits**

GPS: Railroad and Other Transportation Applications

Land Transportation Applications

- **Rockwell transportation applications include:**
  - Railroad Electronics:
    - Train Control, Cab Electronics, Condition Monitoring, Traffic Planning
  - Transit Systems:
    - Passenger Information Systems, Asset Management Systems
  - Highway Transport Electronics:
    - Mobile Communication Systems, On-Board Computing
  - Automotive Electronics:
    - Driver Information Systems

GPS: Railroad and Other Transportation Applications

Railroad Electronics Applications

- **Train Control**
  - Authority Enforcement
  - Headway Control
- **Cab Electronics**
  - Train Handling
  - Event Recording
  - Training & Simulation

GPS: Railroad and Other Transportation Applications

Railroad Electronics Applications (con't)

- **Condition Monitoring**
  - Maintenance Planning
  - Fuel Tax & Emissions Reporting
- **Traffic Planning**
  - ETA generation
  - Advanced Meet / Pass Planning

Transit System Applications (bus / light rail)

- **Passenger Information Systems**
  - Passenger Tracking systems
  - Passenger Assistance systems
  - Platform Announcement systems
  - Emergency Response systems
- **Asset Management Systems**
  - Condition Monitoring systems

GPS: Railroad and Other Transportation Applications

Highway Transport Applications

- **Mobile Communication Systems**
  - Truck Dispatch systems
  - Emergency Response systems
- **On-Board Computing**
  - Condition Monitoring systems
  - Fuel Tax reporting (state line crossing)

GPS: Railroad and Other Transportation Applications

Automotive Electronics Applications

- **Driver Information Systems**
  - In-vehicle Navigation systems
  - Emergency Response systems

GPS: Railroad and Other Transportation Applications

Summary

- **GPS is a tool that can:**
  - Add-value for equipment suppliers
  - Increase competitiveness for users
  - Improve service for end customers

Utilizing Transit Applications of GPS Technology in Railroad Systems

Presented By:
Howard Shore, Project Manager -
Baltimore Light Rail Signal Preemption Program,
Orbital Sciences Corporation

As Part of:

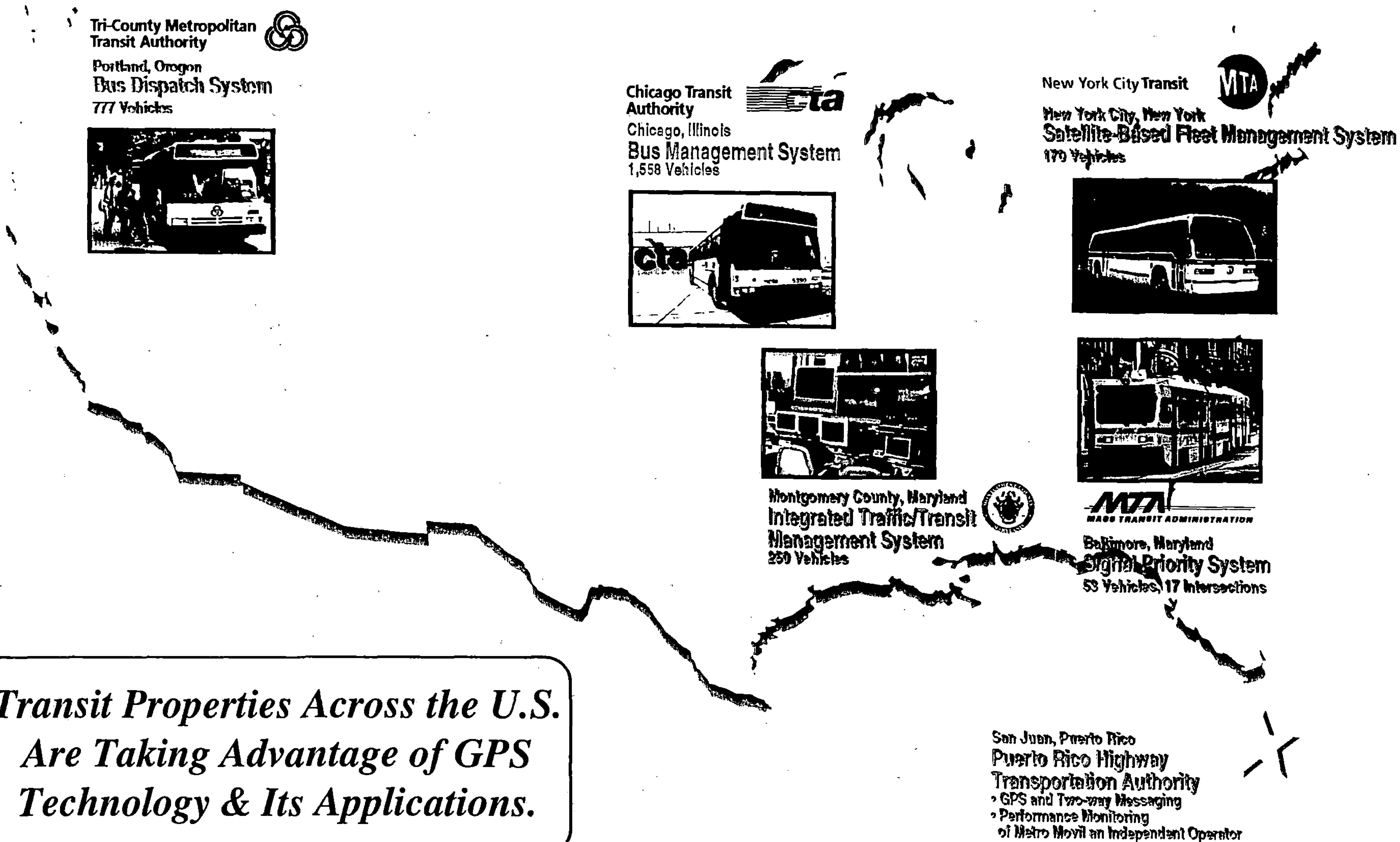
GPS and Its Application to Railroad Operations: A Technical Symposium

Hosted By:
The Federal Railroad Administration

November 14-15, 1996

GPS Technology in Transit Applications

Orbital Sciences Corporation OSC



Transit Properties Across the U.S. Are Taking Advantage of GPS Technology & Its Applications.

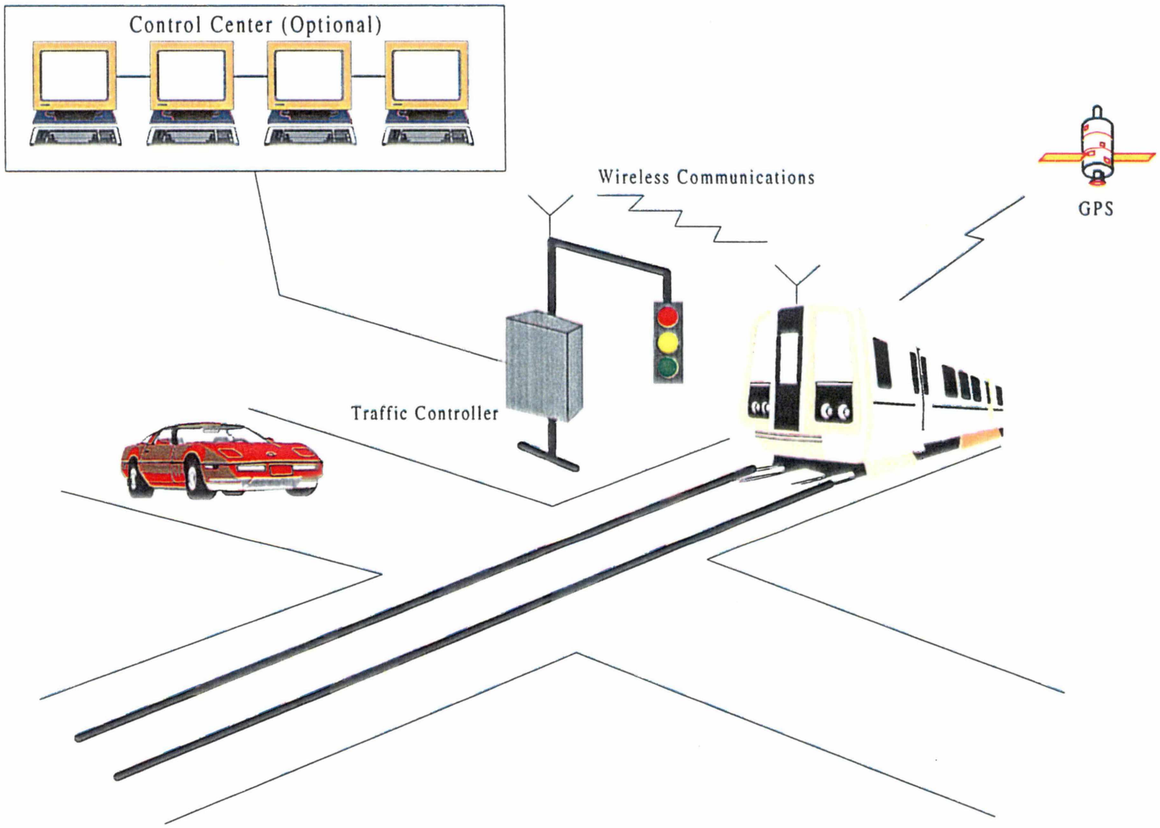
- When GPS Position is Known...
  - Emergency Assistance
  - Vehicle Tracking & Mapping
  - Next Stop Message Signs and Annunciators
  - Traffic Signal Preemption

- When GPS Position and Scheduled Position are Known...
  - Schedule Adherence
  - Run Optimization, Adjustments, and Changes
  - Traveler Information Systems

Rail Systems Can See Immediate Benefits From GPS Train Location. Adding Schedule Information Increases the Ways that GPS Data Can Be Used.

GPS Data Improves Light Rail Performance

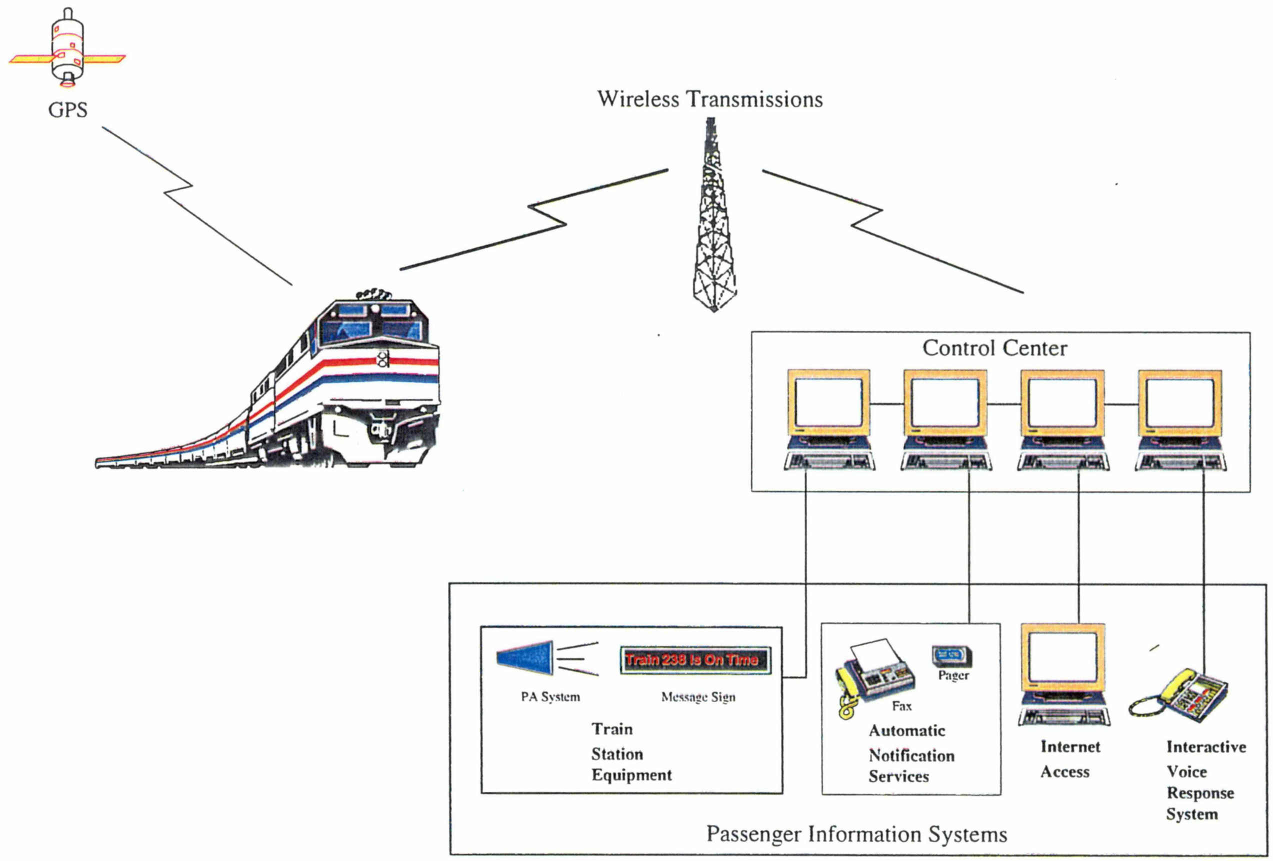
Orbital Sciences Corporation



Light Rail Vehicles Pass Through Preempted Intersections Without Stopping. When Light Rail Is Not Present, Traffic Flow for Automobiles is Maximized.

GPS Data Helps Keep Rail Travelers Informed

Orbital Sciences Corporation



Riders Access Real-Time Data From Many Sources. Railroad Personnel Manage Schedule Changes While Computers Handle Information Flow.

GPS Solutions Available Now For Railroads

Orbital Sciences Corporation OSC

- Low Cost
  - GPS Receivers From Many Suppliers
  - Existing Systems Provide 'Off-the-Shelf' Solutions
  - 'Shrink-Wrapped' Software Applications
- Convenient
  - User-Friendly Vehicle and Command Center Systems
  - Minimal Disruption of Rail Service During Installation
  - Benefits are Immediate
- Proven
  - GPS Constellation Has Been Operational for Over 10 Years
  - Nation's Largest Transit Properties are Using GPS Systems
  - Consumer GPS Products are Readily Available

The Expanded Role of GPS in Commuter Rail Systems

Douglas Toth, Ph.D.
GeoFocus, Inc.
1155 NW 13th Street
Gainesville, FL 32601
(352)336-8444

ABSTRACT

Beyond the standard tracking needs, commuter rail systems can use information from the Global Positioning System (GPS) to assist in scheduling, improve customer service, monitor and record system operations during normal and abnormal conditions, and provide input to visual and audible warnings for positive train separation and track cautions. Location, time, and speed information are key GPS provided parameters that can be collected for evaluation and subsequently used as inputs to a vehicle information platform.

A recent pilot study for the Tri-County Commuter Rail Authority (Tri-Rail), located in South Florida, demonstrated how collected GPS data provide input into a rail information system that assists every level of the mass transit operation.

The Tri-Rail has identified the need to improve system scheduling and customer service. The recorded GPS information is displayed in real-time and can be replayed at a later time to evaluate existing or proposed operational schedules. Future scheduling changes can be based on statistical comparisons between arrival times and train schedule for each rail stop and adjusted accordingly. Valuable information such as train number, mile marker, speed, next station, estimated time of arrival, and time comparison to schedule provide customer service with real-time performance information which can be relayed to the customers via operator, automated telephone messaging, World Wide Web, or displayed on location at the train stations.

The Tri-Rail operator, Herzog Transit Services Inc., will use Global Positioning System data to provide operations with a means to monitor present and historic events for purposes of incident reports, train delays, and a method to analyze locomotive performance parameters. Rail system safety can be enhanced by continuous interactive monitoring of positive train separation distances and existing rail cautions. When adverse circumstances arise, visual and audible alarms can inform the engineer of the situation and allow a means for the engineer to communicate and acknowledge messages with the base station.

The Expanded Role of GPS in Commuter Rail Systems

November 14, 1996

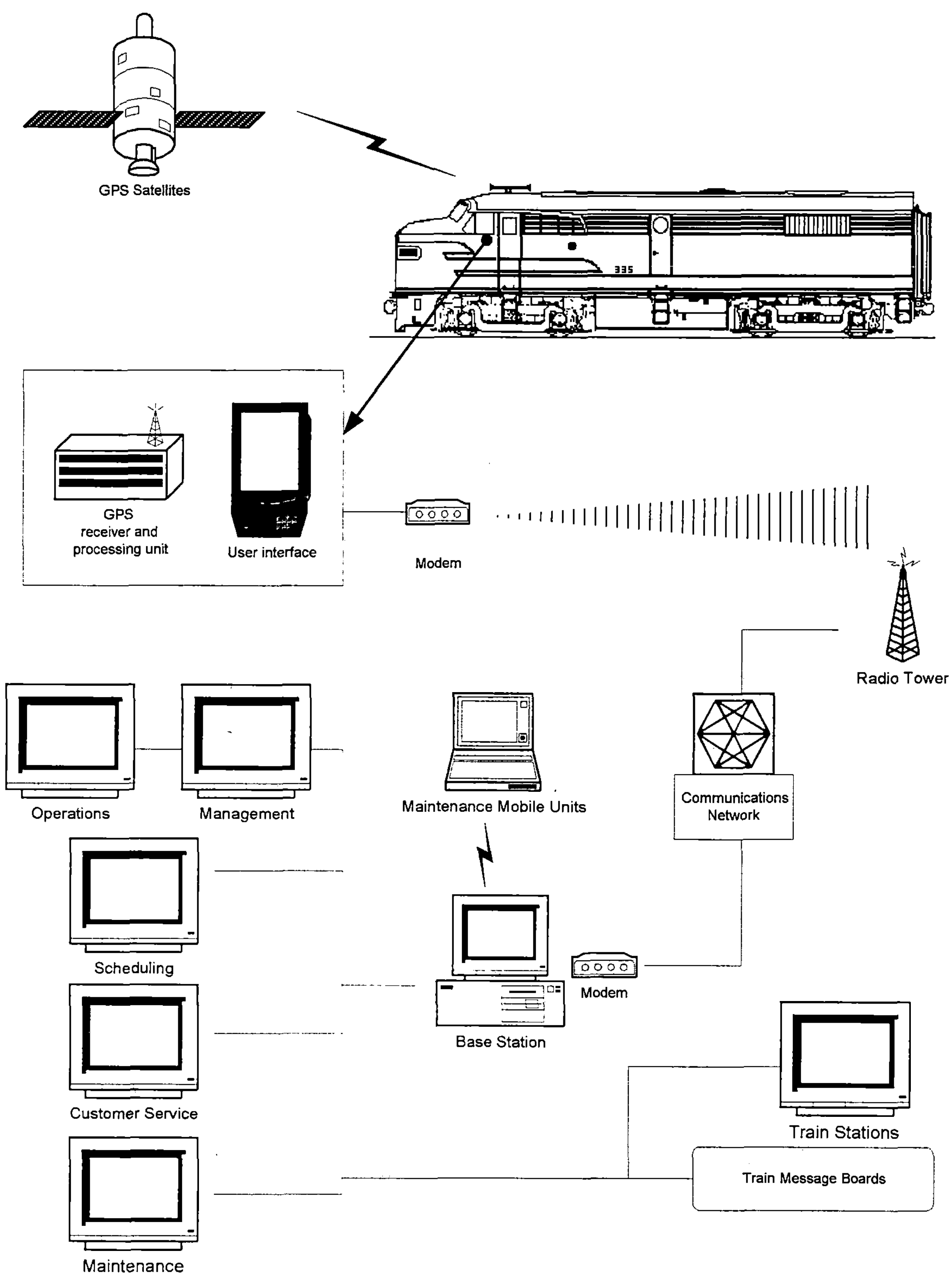
A WILLIAMS CONTROLS COMPANY

Valuable Uses of Rail GPS Data

(Location, Time, and Speed)

- Operations
- Scheduling
- Maintenance
- Customer Service
- Rail Station Display
- Management
- Training
- Safety
- Emergency Management

A Rail Information System

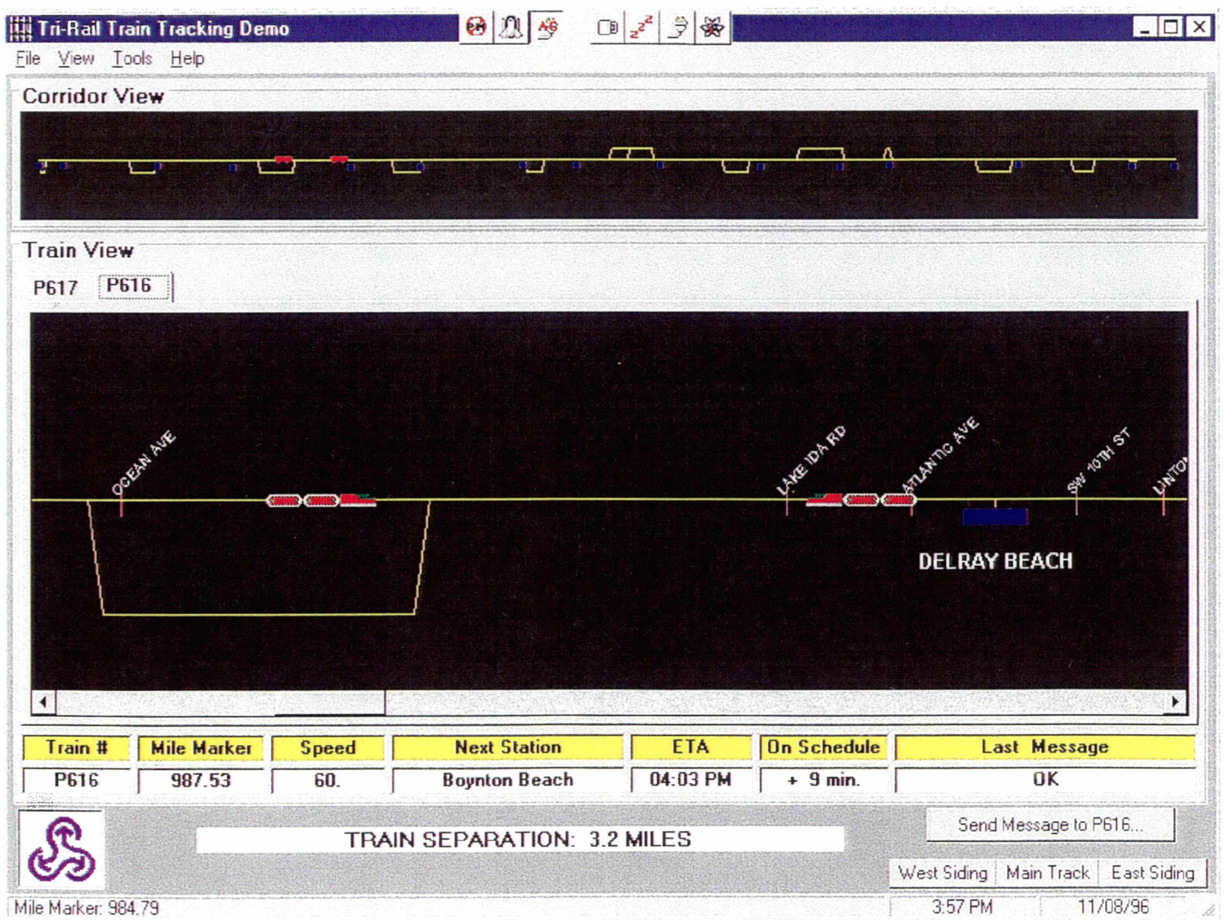


Train Terminal Functionality

- GPS data collection
- GPS data conversion
- Transmit train information including
  - train ID
  - train location
  - train speed
  - time of event
  - routine messaging
    - location (mile-post), time, speed (mph)
    - arriving at station, departing station
    - on main tracks, on siding
  - non-routine messaging
    - delays, track obstruction
  - emergency messaging
    - accidents, needs for assistance, injury report, and train status

Base Station Functionality

- Receive messages from train units
- Transmit messages to trains
- Display train locations
- Graphical user interface and display of GPS information for operations



- # Display of current schedule

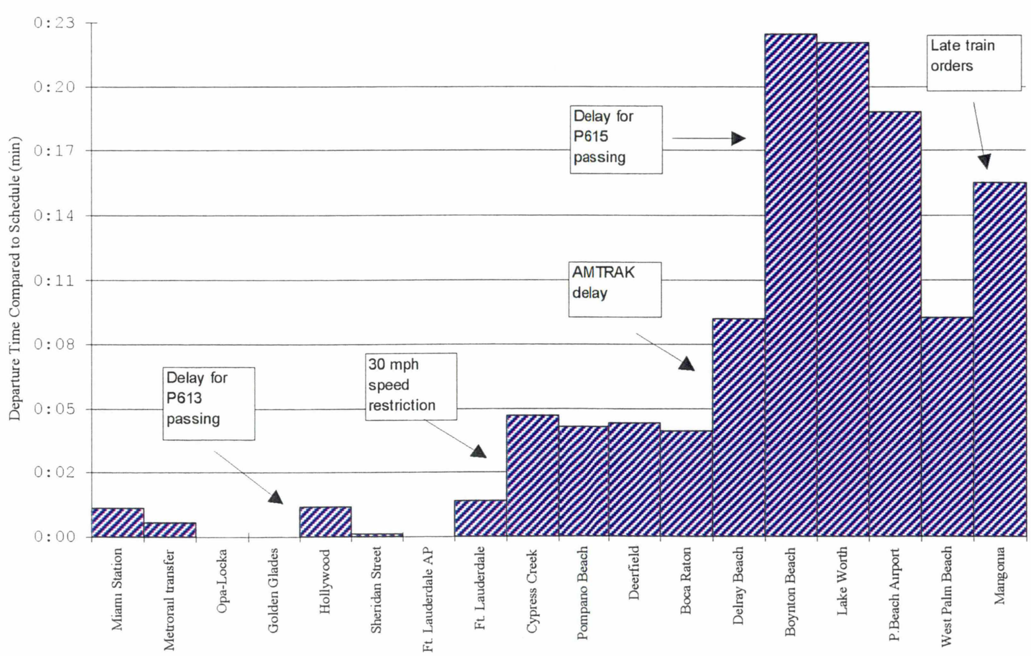
Train Schedules

Weekdays - Southbound | Weekdays - Northbound | Weekends - Southbound | Weekends - Northbound

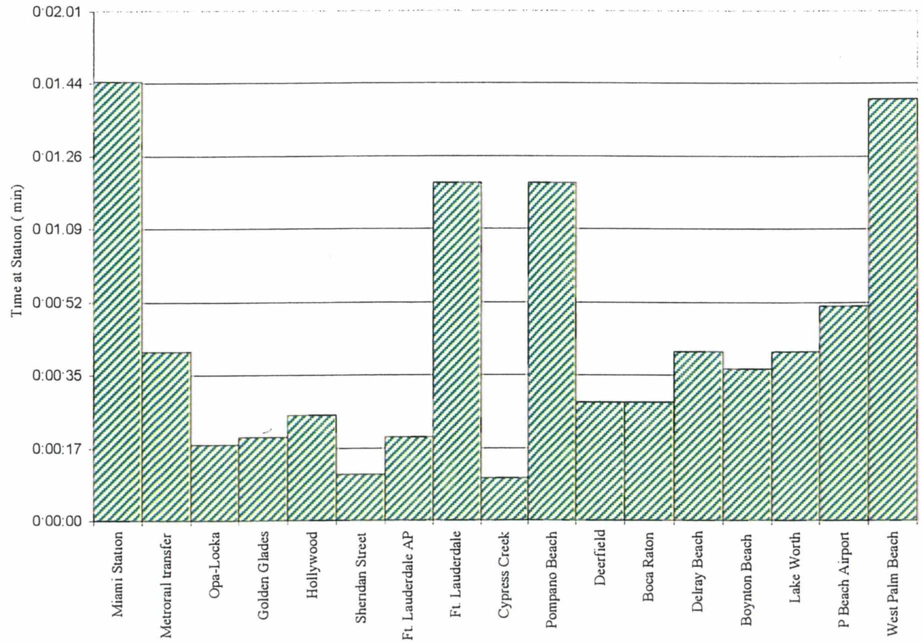
STATION	MORNING							AFTERNOON				EVENING			
Station	P601	P603	P605	P607	P609	P611	P613	P615	P617	P619	P621	P623	P625	P627	P629
Mangonia Park	4:34	5:38	6:41	7:45	9:08	10:23	11:49	2:14	3:14	4:33	5:41	6:49	7:51	8:59	10:00
West Palm Beach	4:38	5:42	6:45	7:49	9:12	10:27	11:53	2:18	3:25	4:33	5:41	6:49	7:51	8:59	10:00
Palm Beach Airport	4:45	5:49	6:52	7:56	9:22	10:34	12:00	2:28	3:31	4:37	5:45	6:53	7:55	9:03	10:04
Lake Worth	4:51	5:55	6:58	8:02	9:28	10:40	12:06	2:34	3:41	4:44	5:52	7:00	8:02	9:10	10:11
Boynton Beach	5:01	6:05	7:08	8:12	9:38	10:51	12:16	2:42	3:47	4:50	5:58	7:06	8:08	9:16	10:17
Delray Beach	5:06	6:10	7:13	8:17	9:43	10:56	12:21	2:47	3:55	5:01	6:08	7:16	8:18	9:26	10:27
Boca Raton	5:13	6:17	7:20	8:24	9:50	11:03	12:28	2:54	4:00	5:07	6:13	7:21	8:23	9:31	10:32
Deerfield Beach	5:18	6:22	7:25	8:30	9:55	11:08	12:36	2:59	4:07	5:14	6:20	7:28	8:30	9:38	10:39
Pompano Beach	5:27	6:31	7:34	8:39	10:04	11:17	12:45	3:09	4:12	5:19	6:25	7:33	8:35	9:43	10:44
Cypress Creek	5:36	6:40	7:43	8:48	10:13	11:26	12:54	3:18	4:22	5:29	6:35	7:43	8:45	9:53	10:54
Fort Lauderdale	5:44	6:48	7:51	8:56	10:21	11:34	1:01	3:25	4:31	5:38	6:44	7:52	8:54	10:02	11:03
Fort Lauderdale Airport	5:48	6:52	7:55	9:00	10:25	11:38	1:05	3:29	4:38	5:45	6:51	7:59	9:01	10:09	11:10
Sheridan Street	5:52	6:56	7:59	9:04	10:29	11:42	1:09	3:33	4:42	5:49	6:55	8:03	9:05	10:13	11:14
Hollywood	6:02	7:06	8:09	9:14	10:37	11:51	1:18	3:42	4:46	5:53	6:59	8:07	9:09	10:17	11:18
Golden Glades	6:07	7:11	8:14	9:19	10:42	11:56	1:23	3:46	4:56	6:03	7:09	8:17	9:19	10:27	11:28
Opa-Locka	6:15	7:19	8:22	9:27	10:50	12:04	1:31	3:54	5:01	6:08	7:14	8:22	9:24	10:32	11:33
Metrorail Transfer	6:25	7:29	8:32	9:37	11:00	12:14	1:41	4:04	5:09	6:16	7:22	8:30	9:32	10:40	11:41
Miami Airport	6:22	7:23	8:28	9:55	11:22	12:26	1:36	4:04	5:19	6:26	7:32	8:40	9:42	10:50	11:55

- # Display of performance to schedule

11/05/96 Departure Times for P612

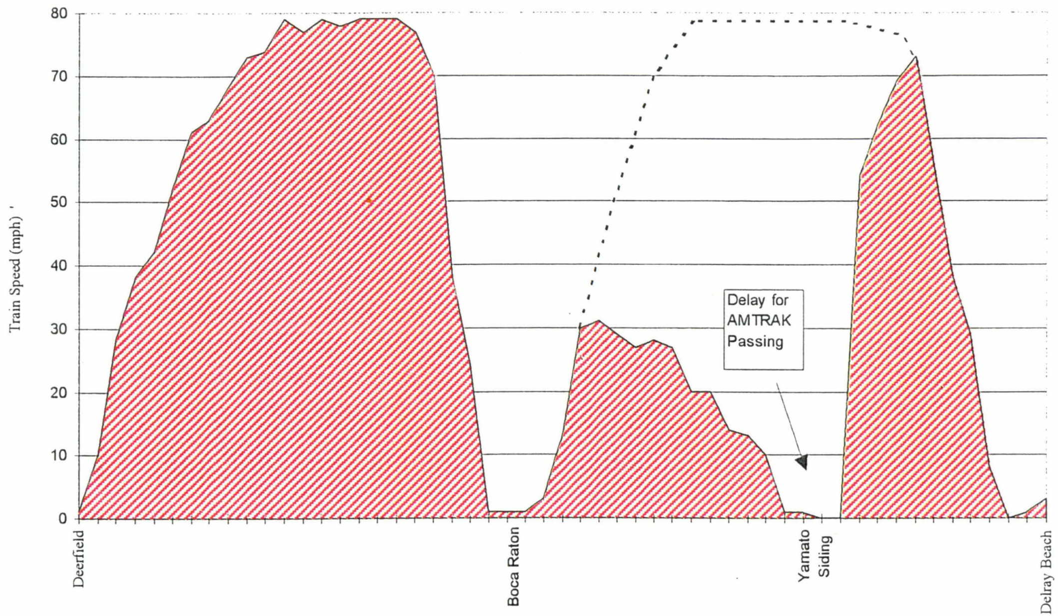


11/05/96 Time at Stations for P612



- Display of operational parameters

11/05/96 P612 Operating Speed



- Display of operational performance

Condition Monitoring & Maintenance Planning

GPS and GIS Applications

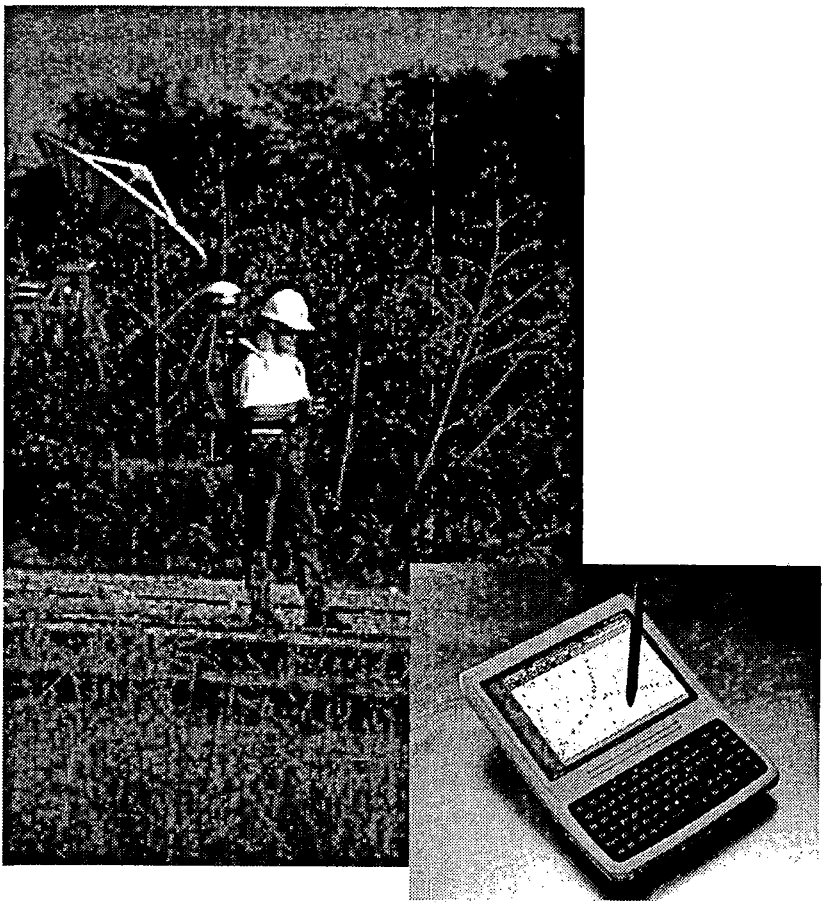
Presented by Kevin Kesler
ENSCO, Inc.
November 14-15, 1996

In today's railroad environment, about the only thing one can be certain of is change.

New technologies, introduced in the face of ever increasing competition, shape the future of the railroad industry.

In The Future...

- All inventory, maintenance and inspection operations on the railroad will be guided, tracked, stored, and reported in terms of latitude and longitude.
- GPS, GIS, and digital data communications will link railroad managers and the field inspection/maintenance teams.



ES96-0078

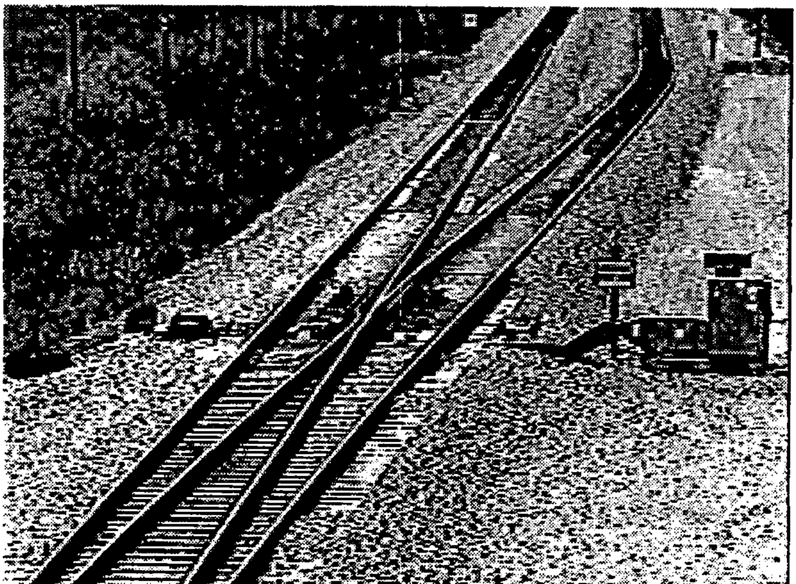
Today's Railroad

- More than 40% of the nation's freight moves by rail.

- The majority of rail traffic moves on privately owned, dedicated rights-of-way.

- The information flow necessary to support the operation and maintenance of the typical modern railroad is hidden from view.

ENSCO, Inc.
1996

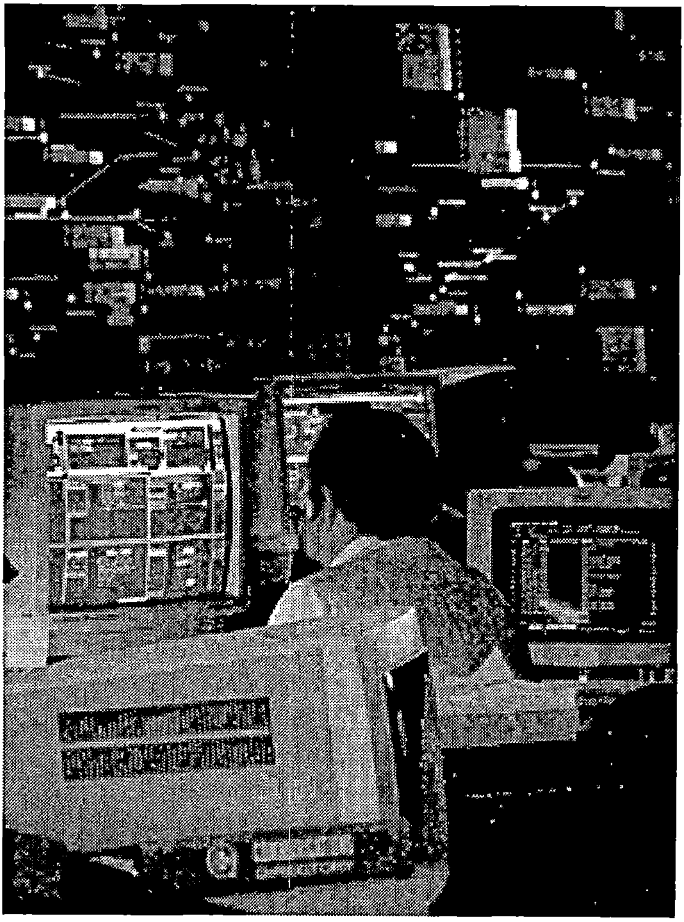


ES96-0078

Current Status

- **Fact:**
  Electronic data communications have replaced the vast paper flows associated with waybills and invoices for shipping cars, and for billing customers.

- **Fact:**
  On many railroads the headquarters' MIS systems for corporate networks and train control systems are state-of-the-art.



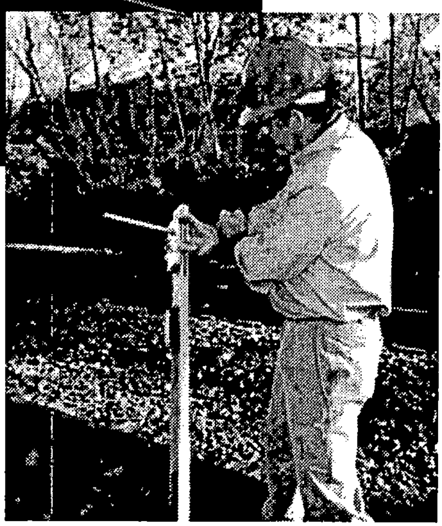
ES96-0078

Current Status

- **Fact:**
  Most of the processes that are of critical importance to the railroad occur in the field.

- **Fact:**
  Information Systems used to manage field maintenance and inspection have evolved into a patchwork of radio, cellular, fax, and hand written communications.

(continued)



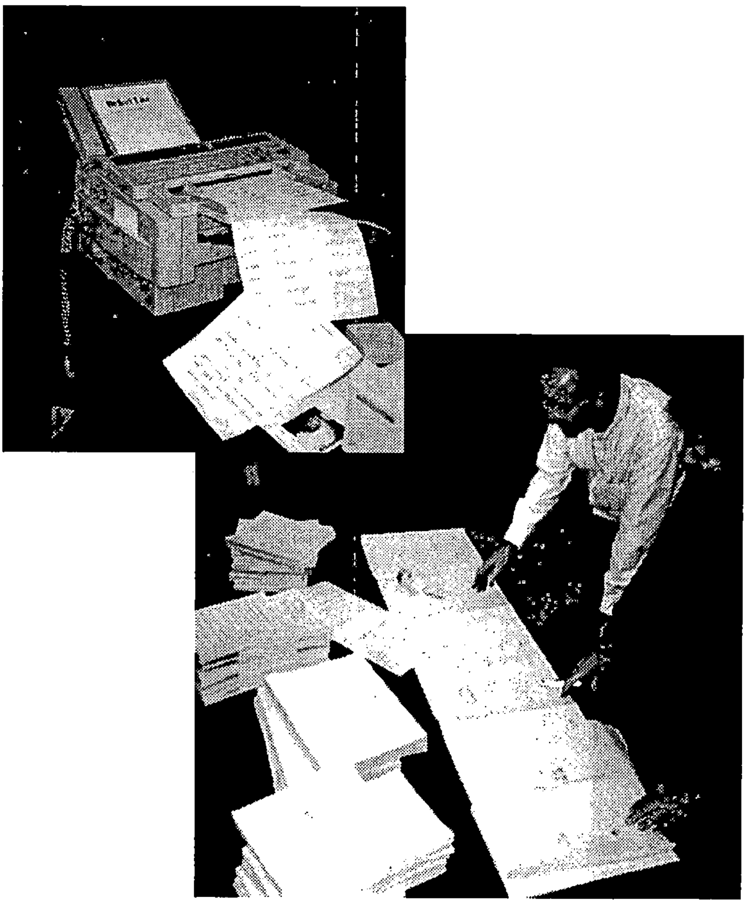
ES96-0078

Current Status

- **Fact:**
  Advanced inspection systems accurately and efficiently detect track conditions in need of attention.

- **Fact:**
  However, maintenance personnel still must use a great deal of detective work to relate these conditions back to the track itself.

(continued)

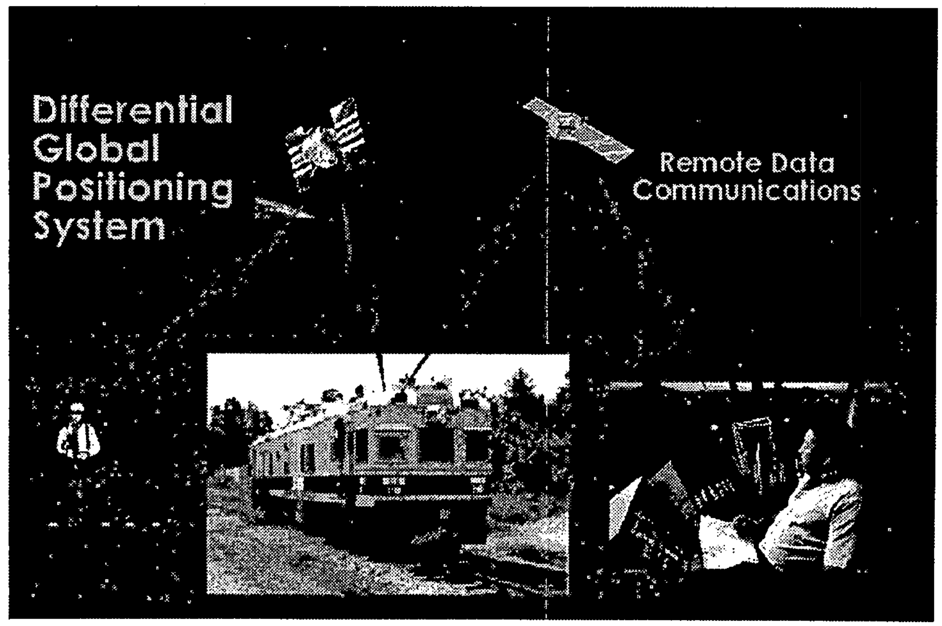


ES96-0078

Field Data Communications and MIS Systems

- The railroad industry has over $54 billion in assets, most of which is in the field.

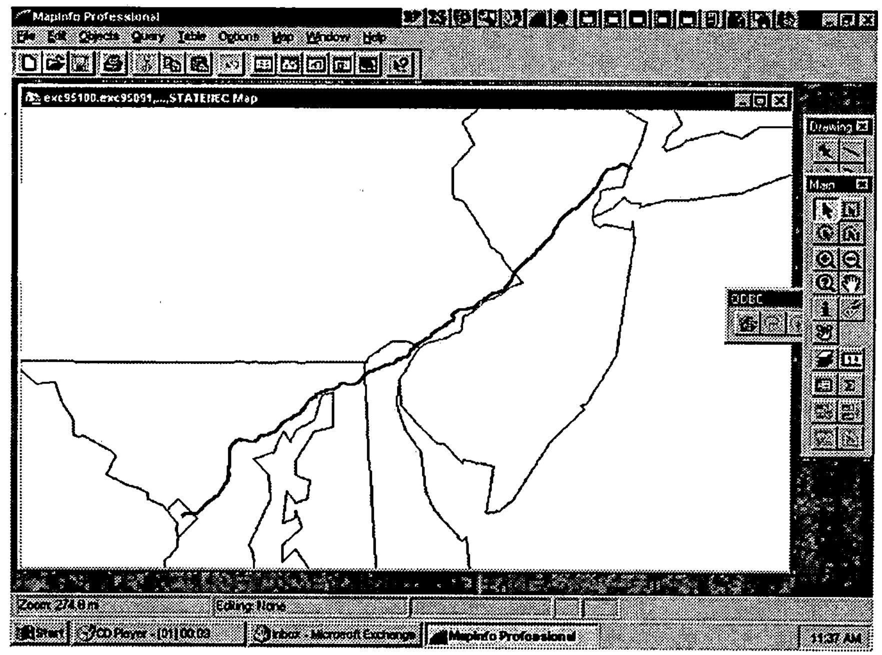
- Improved systems and techniques for communicating and managing information from the field must be developed to assure the long-term growth and stability of the industry.



Steps to Advancement

- Geographical information systems enable railroads to organize and evaluate track condition reports and maintenance plans.

- Using GIS, the railroad industry can properly balance maintenance priorities against projected traffic demands.



Progress

- Open architecture designs for remote locomotive monitoring systems
- High-speed automated track inspection systems
- GIS systems to plan and track inspection/maintenance programs
- Global Positioning Systems with Differential Correction to pinpoint problem area of track
- Global Positioning Systems to help MOW forces quickly locate and correct problems following inspection

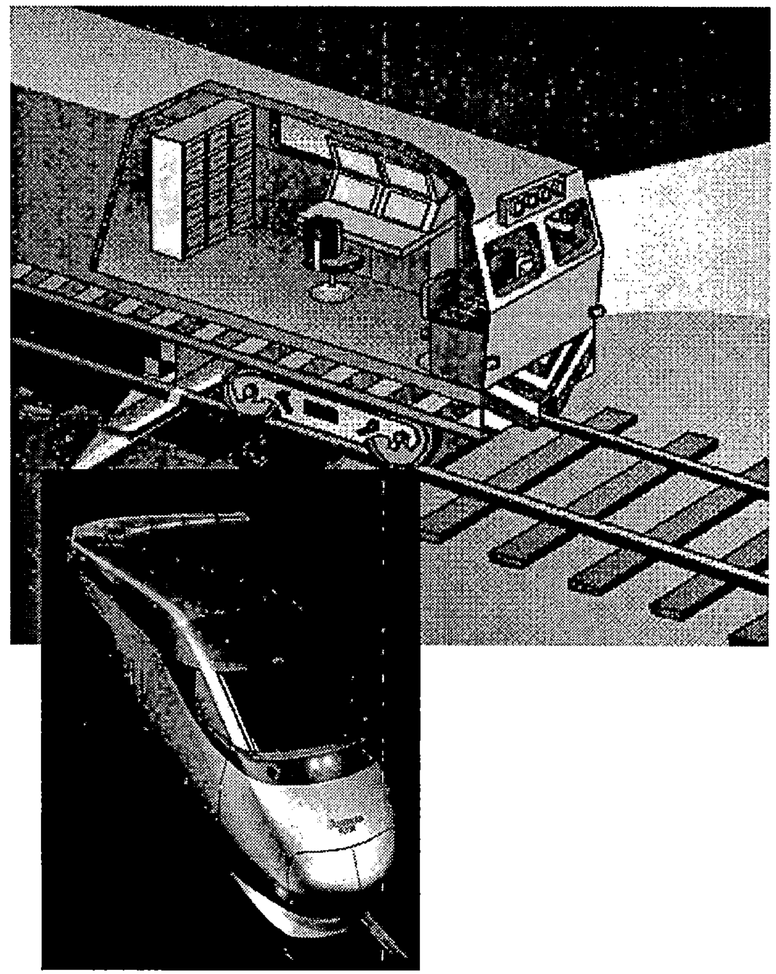
How ENSCO Can Help

- As a proud supplier of technology to the railroad industry for more than 25 years, ENSCO continues to help railroads and suppliers alike to better define which technology can help meet their needs and select the most appropriate path to meet those needs.

Challenge for the Future

- For the railroads, their suppliers and the regulatory agencies:

  Create an environment that will accommodate change, identify appropriate technology, and use it to the best advantage of the industry and the public it serves.



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GPS R&D on JR Freight, JR East and RTRI

Yutaka Hasegawa
GM, Technical Support Div.,
Railway Technical-Research Institute of Japan

1. Introduction

Being a very small size and low cost sensor for positioning, the GPS receiver is now widely used for car navigation or survey. The railway application of GPS has just begun and it is eagerly investigated worldwide. Some instances in Japan are presented here.

2. Traffic supervision system of JR Freight

(1) Background

JR Freight is one of JR companies which have been established with the privatization of Japan National Railway in 1987. This company is only in charge of the freight transportation service in the whole country, operating freight trains on the infrastructure owned by six passenger railway companies. The traffic dispatchers of JR Freight have indirectly to supervise train operation with the information provided from passenger railways' dispatchers and to send their dispatch commands to crews on freight trains via those other companies dispatchers because JR Freight has no facilities of its own such as CTC and a radio communications system. The JR Freight has developed a system described here as its own dispatch facilities, which has started its service in November, 1996.

(2) System functions

The system functions are to display the following information on consoles of central dispatchers and terminals installed at freight stations:

(a) train positions

(b) train delay time

This information is updated every 30 minutes on normal traffic or 5 minutes on irregular one. The central dispatcher console uses a workstation, displaying train positions on a route map. The character displays provided for the container reservation system are used as the terminal of a station.

(3) System configuration

The configuration of the system is shown in Fig. 1. The network center, on-board systems and the satellite communications system are available from the OmniTRACS.

The communications line from the network center to the JR Freight center is a personal circuit. The network connecting the JR Freight center to dispatch consoles and to terminals is a packet network of JR group. This system has started its service on two main lines from Tokyo to Kyushu. with the number of terminals about 200, and that of trains equipped with an on-board system 220. Fig.2 is a photograph of antennas set on a train roof, where the round shape one is for GPS and the square one for communication. The on-board display and the keyboard installed in the driver cab are shown in Fig.3. The train operation schedule is stored in a memory card inserted into a slot of the display box. That on-board dislay is planed to give a dispatch command to train drivers in the future expansion.

3. JR East Warning System of Approaching Train to Wayside Workers

(1) Background

In major railways of Japan. it is one of very important subjects to be addressed in the interest of safety to prevent trains in high speed and high density operation from hitting wayside workers engaged in maintenance and construction of track or signalling facilities. It is now a watcher's responsibility to detect trains approaching the work spot. and to give an alarm to his workers . Though several types of alarm systems to assist the watcher's job have been provided. they are seldom used for lack of portability. Therefore East Japan Railway Co. (JR East) is now developing a new warning system[1)] which applies GPS to the detection of train position and working spot with an improved portability.

(1) Outline of the system

The system concept is shown in Fig. 4 Trains are equipped with an on-board system composed of a GPS receiver and a radio transmitter. A watcher of approaching trains carries an alarm terminal consisting of a display panel, a GPS receiver. a radio receiver and a processor. Fig. 5 is an illustration of an alarm terminal and its display. The on-board system transmits the train position every 2 seconds by radio. The alarm terminal estimates the distance between trains and itself from position data. and issues a warning sound if the distance comes close to a predetermined critical value.

(2) Brief specification

The data length of a frame transmitted from a train is 369 bits including 128 information. error correcting code and synchronous bits. The radio channel is only one of 400Mhz and the data transmission speed is 2400bps. A train transmits data within a specified time slot of the channel corresponding to its position in order to avoid collision of transmission from plural trains.

The alarm terminal issues a sound when any train approaching to it enters into a given zone of distance(1, 1.5 or 2km), stopping the warning when the train moves away past the first 50m point from the nearest point to the terminal.

(3) Function test

A system test was carried out on a service line last year. Ten sets of the on-board systems were mounted on train cabs and the same number of alarm terminals were located at various places along the line.. It is assured in this test that the system fulfills specified functions including supervisory ones against failures of components such as radio transmitter and receiver.

Hereafter. it is planned to confirm the endurance and the reliability of a smaller-sized system revised for practical use and to improve its performance such as radio transmission speed and water-resisting qualities in a long term test.

4. Extra sensor for ATP

(1) Background

The major ATP of JR is now a type of spot coils shifting the resonance frequency. The system, called ATS-S. rings a bell sound when the signal is red, causing the emergency brake to act regardless of the train speed unless the driver handles the brake within 5 seconds. On the other hand. a transponder-based ATP called ATS-P has been introduced recently on high traffic lines. It receives a signal aspect and distance data from the transponder, and supervises the train speed according to a brake curve generated on-board. The intelligence is enhanced. but the cost of ATS-P becomes much higher than ATS-S. Therefore. RTRI has developed an on-board information-based ATP named ATS-SP[2),3)] which can work as the transponder-based ATS-P using the spot coil of ATS-S. The configuration of ATS-SP is shown in Fig. 6. Being able to receive no information other than a signal aspect from the spot coil. ATS-SP system retrieves the distance data from its on-board memory using location of the spot coil as a search key. So the on-board system has always to sense the train running position in order to determine the location of a spot coil when the train passes on it. The mechanism sensing train positions mainly depends on a rotation counter of axes and on location data of special spot coils installed at exit points from a rolling stock yard or a large station. It is, however. not able to sense the position after loss of current position on account of the on-board system down or a long slip of wheel. It has been proposed to apply GPS to an extra sensor which roughly restores a current position. once lost. and a relevant performance test[4)] was carried out in 1991-92. On the other hand. a new train control system named CARAT[5),6)] has proposed a function that trains send an alarm to terminals of wayside workers(Fig. 7). A survey of the accuracy of GPS positioning has been needed, because the terminal transmits its position sensed from GPS to trains.

(2) Outline of test

A set of GPS receiver and micro-computer with a detector of spot coils for ATS-S was mounted on a service train of JR Kyushu. The GPS position data sensed at an interval of 1 second were stored in the micro-computer memory as raw data. Such data gathered total more than 67,000 points in three days. A method of correcting the raw data was also memorized in the micro-computer, because an error was expected to be over 100m. Detecting each spot coil, the correcting algorithm called self-differential calculates the distance between the position from GPS and the standard location of the spot coil as an offset value. This standard location is a mean value of GPS positions sensed in a pre-test. The correcting algolithm revises every GPS position by the offset distance calculated with the latest spot coil.

(3) Analysis of measured data

Number of "bad" codes is about 7% of all data, other bad data being 0.4%. As the major source of error is supposed to be obstacles lying accross the track such as roads and bridges, most of bad data could be removed by excluding data sensed at these places. So the data other than these were analized.

Fig. 8 shows the distribution of error distances without a self-differential between position sensed on a spot coil and its standard location. That of the self-differential is shown in Fig. 9. The error distance including data of 90% is reduced to 50m in the case of self-differential while that of no self-differential is 75m. Fig.10 designates loci of positions sensed in plural tests of the same section, and Fig. 11 is the case of self-differential. The self-differential is considered to have a moderate effect on reduction of errors. It is, however, estimated that position data of GPS are not available for vital control of train like ATP and ATC without more effective method to enhance the accuracy , even if the self-differential is applied. Considering that a position sensor plays an important role in transmission-based train control systems such as ATCS[7], ETCS[8] and ATACS[9], further research and development on positioning should be continued.

5. Conclusions

It is disirable for wide applications in the railway that the accuracy of GPS be made higher. However, the non-vital application in JR Freight is possible with the present performance. With an increase in base stations for the differential GPS , the area where is applicable to railways will spread in Japan. Various other applications will be realized in the future.

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3) Y. Hirao, Y, Hasegawa, H, Nakamura,"TRAIN CONTROL SYSTEMS WITH INFORMATION AND INTELLIGENCE ON BOARD AND THEIR EVALUATIONS", Proc. of IRSE Symposium, session 11, pp5-14(1994)

4) M. Ikeda.. S.Hiraguri, H.Minami,"Evaluation of GPS for its performance to detect Train Position", RTRI Report. 7, 5, pp33-38(1993.5)(in Japanese)

5) Y. Hasegawa."Experimental System of CARAT on Joetsu Shinkansen line",Proc. of IEEE VTC94, pp1113-1116(1994.6)

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8) Silvano Brandi:"The European-Wide Cooperatve Research Project For A Standard Advanced Railway Traffic Management System", Proc. of WCRR96, pp135-142(1996.6).

9) Teruo Kobayashi:"ATACS(Advanced Train Administration and Comminucation System)", Proc. of WCRR96, pp105-109(1996.6).

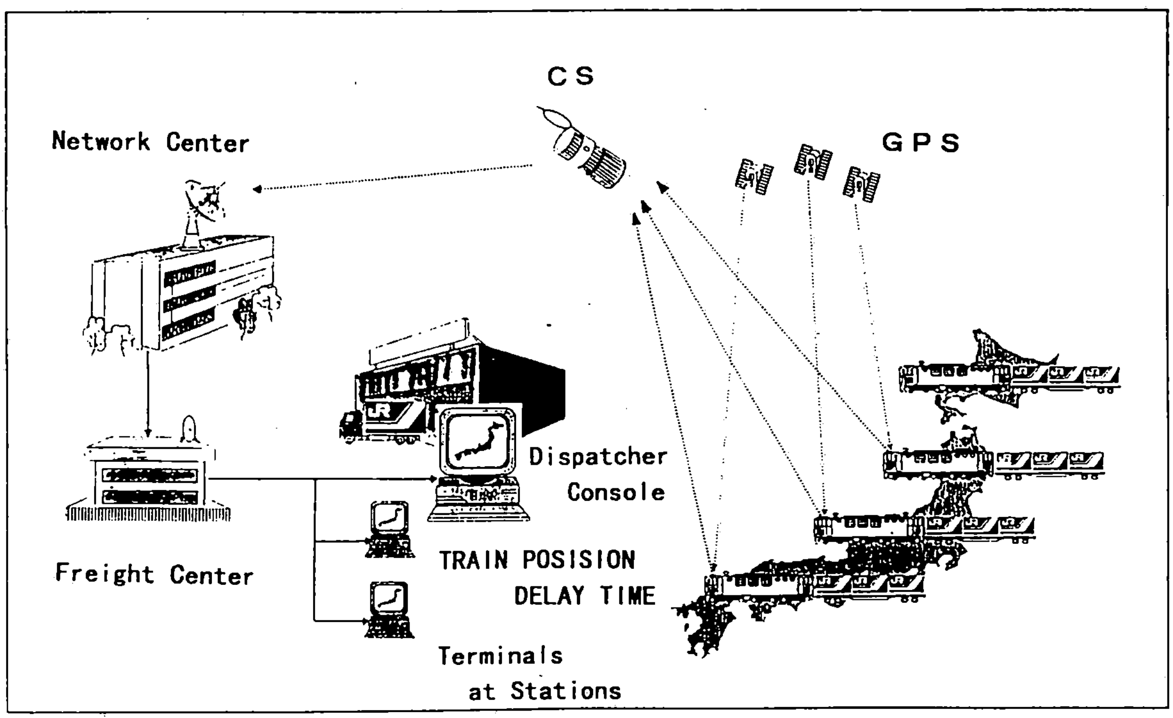


Fig. 1. Configuration of JR Freight system

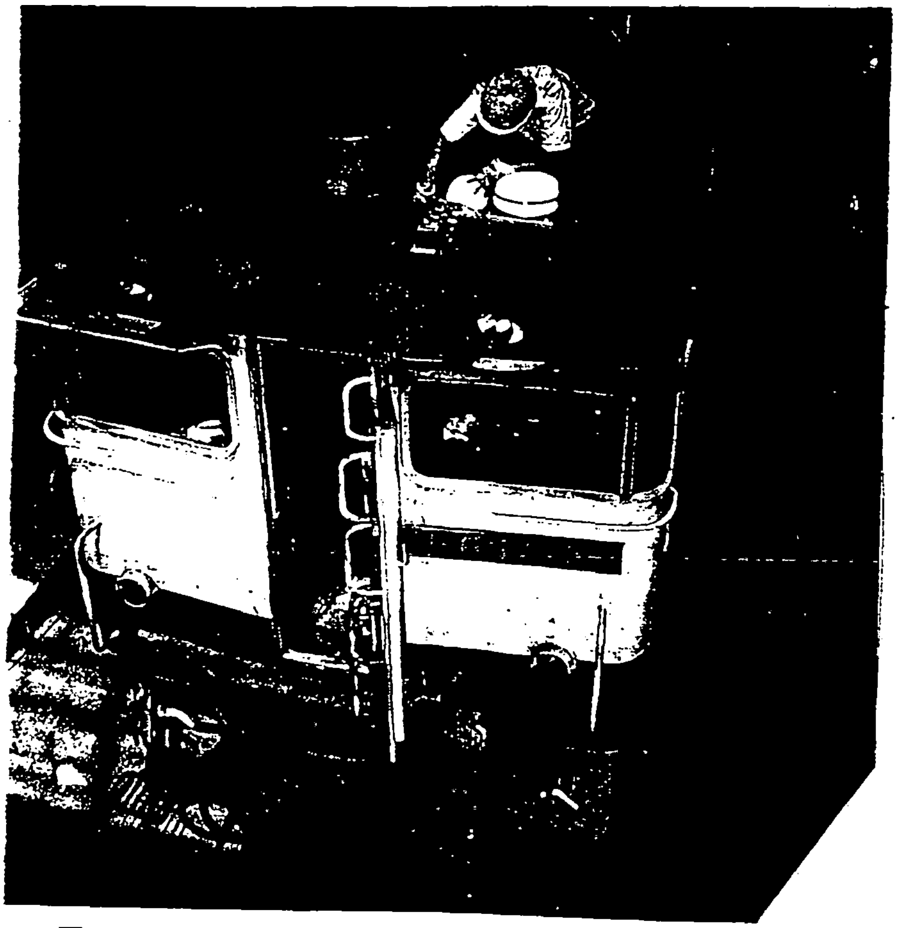


Fig. 2. Antennas set on a train roof

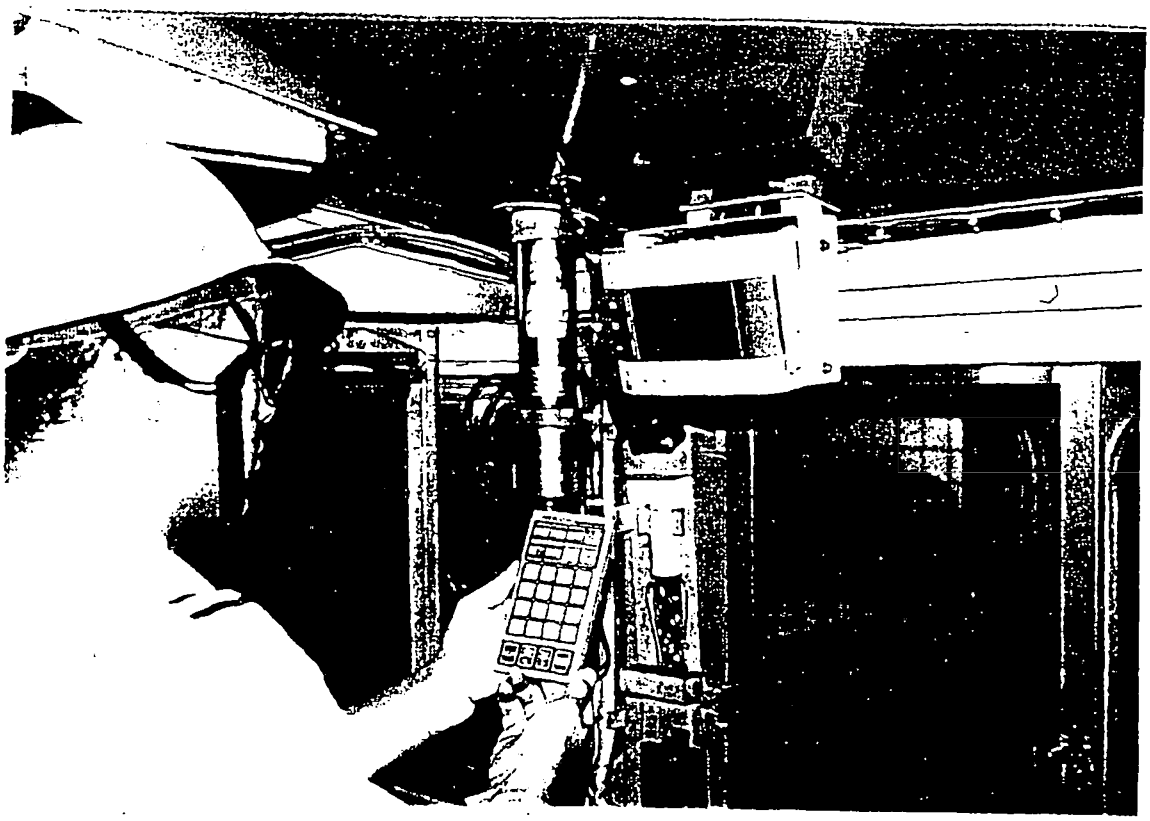


Fig. 3. On-board display and keyboard in a driver cab

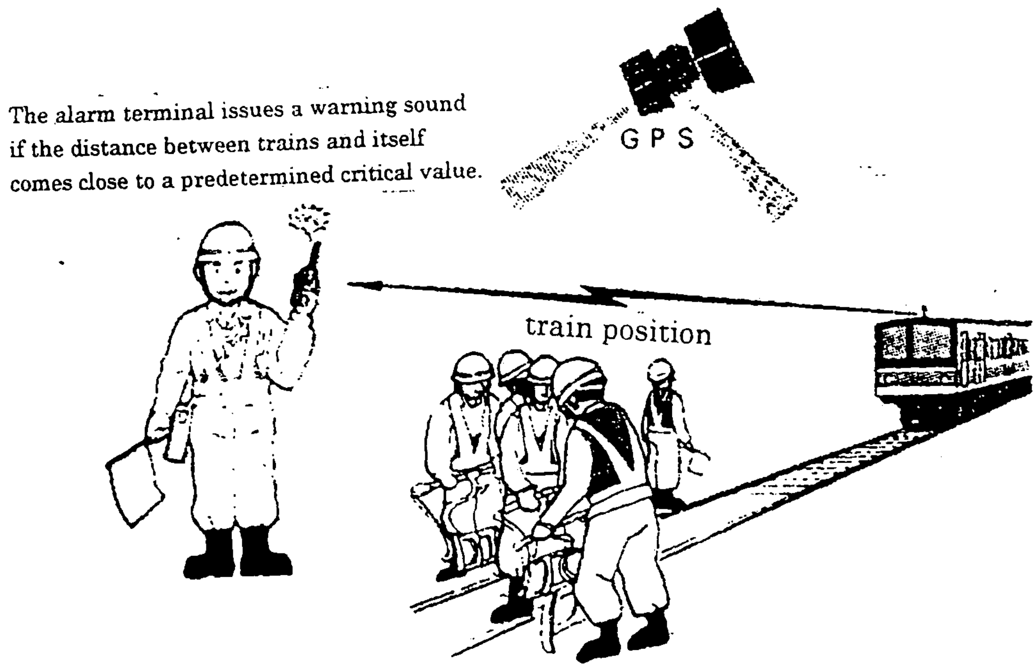


Fig. 4. Schematic of JR East warning system

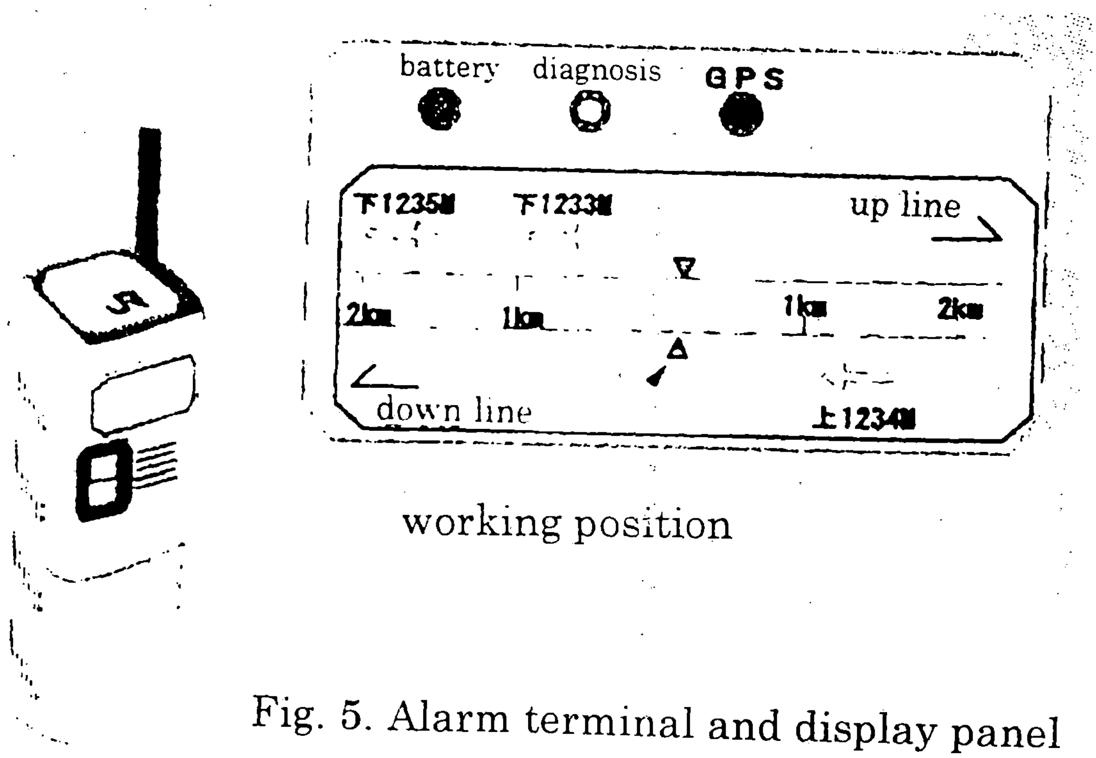


Fig. 5. Alarm terminal and display panel

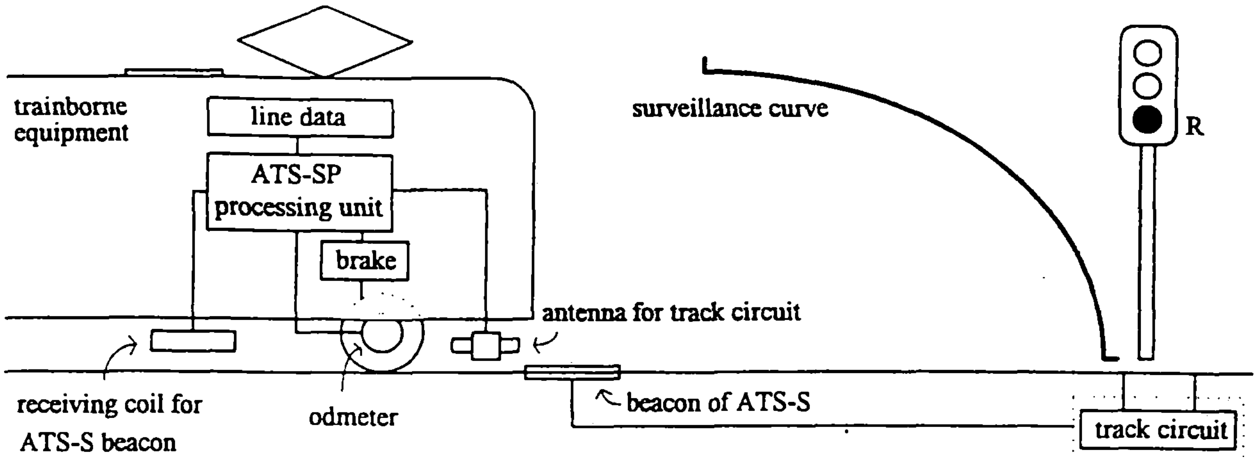


Fig. 6. Configuration of ATS-SP system

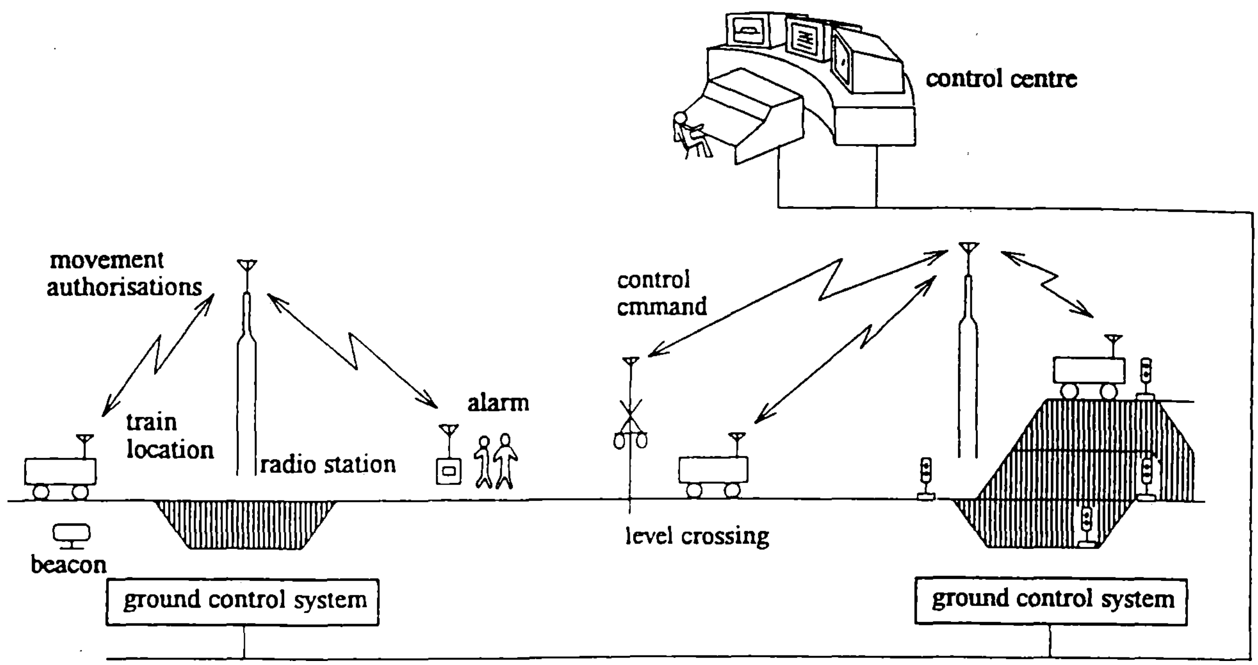


Fig. 7. Concept of CARAT

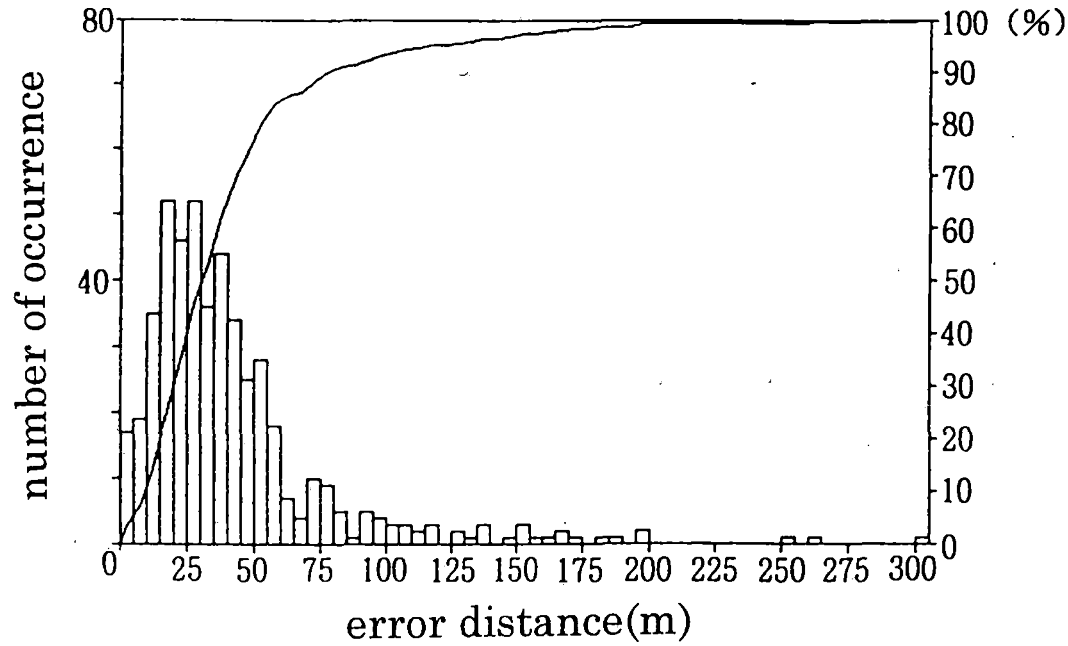


Fig. 8. Distribution of error distances
without self-differential

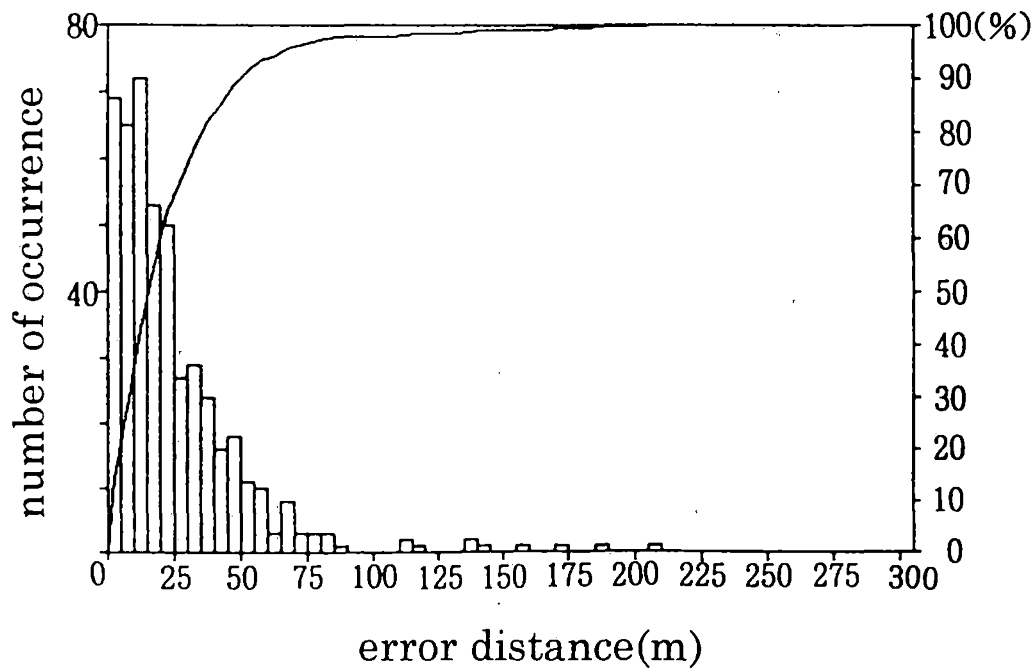


Fig. 9. Distribution of error distances
in the case of self-differential

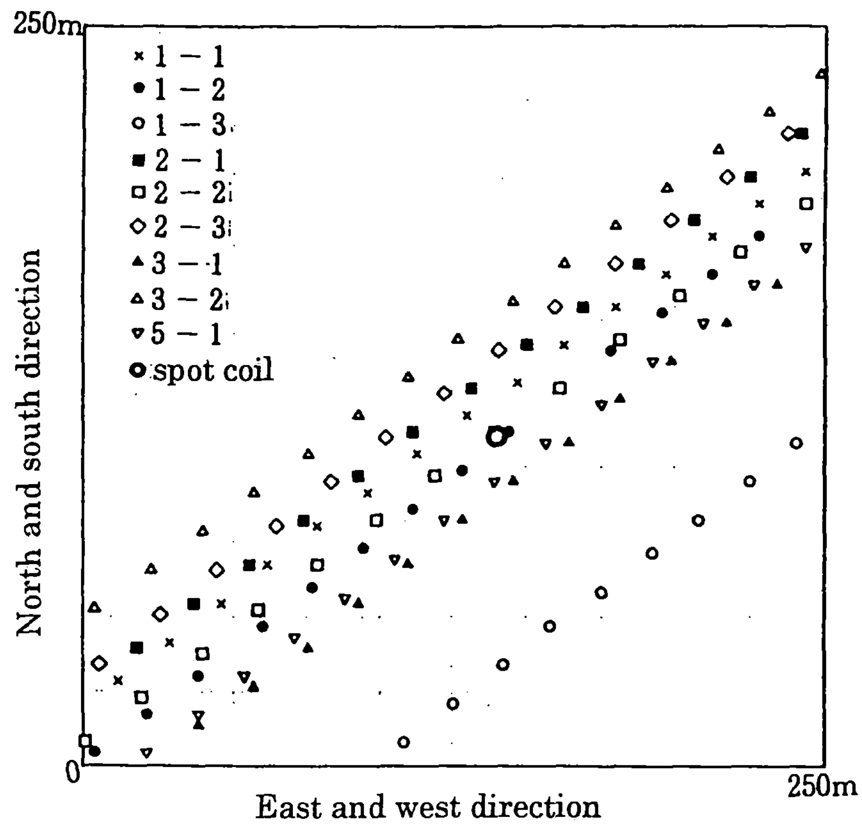


Fig. 10. Loci of train positions without self-differential

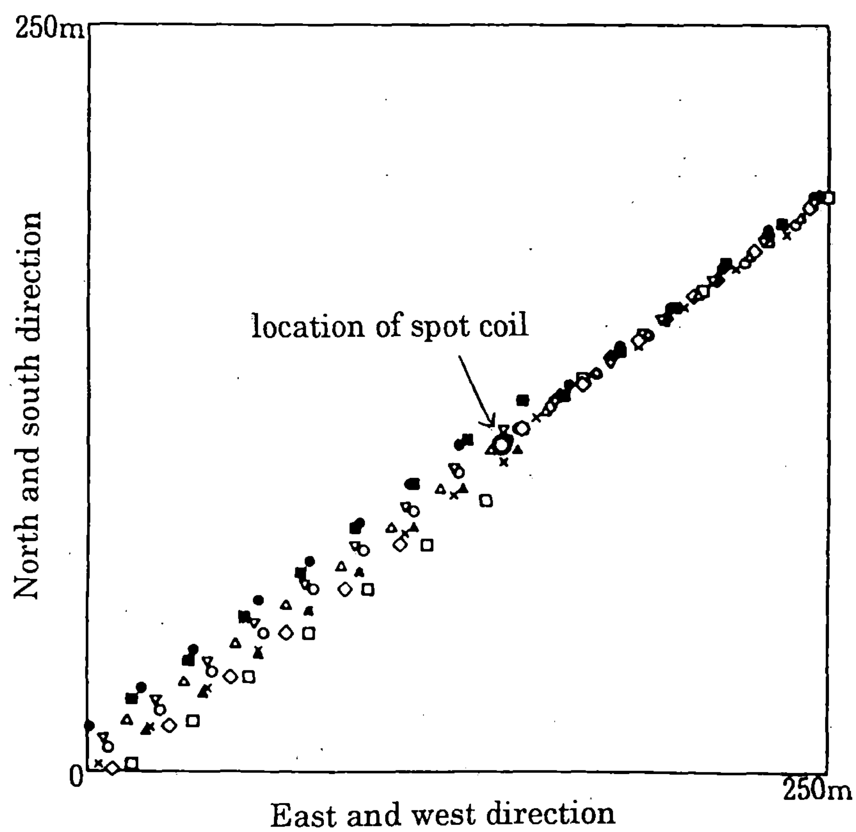


Fig. 11. Loci of train positions
in the case of self-differential

BAD DATA

Ron Lindsey
(904) 366 5399
comarch@aol.com

	40-60's	70-80's	90's
PLAN	MASTER	SEGMENTED	SCHEDULED
TIMELINESS	NONE	EVENTUALLY	DELAYED
EXECUTE	CENTRAL	KIOSK	DISTRIBUTED
I T	BATCH	MAINFRAME ➤ PC	CLIENT / SERVER
COMMUNICATION	WIRED	WIRELESS VOICE	PRIVATE & COMMERCIAL WIRELESS DATA

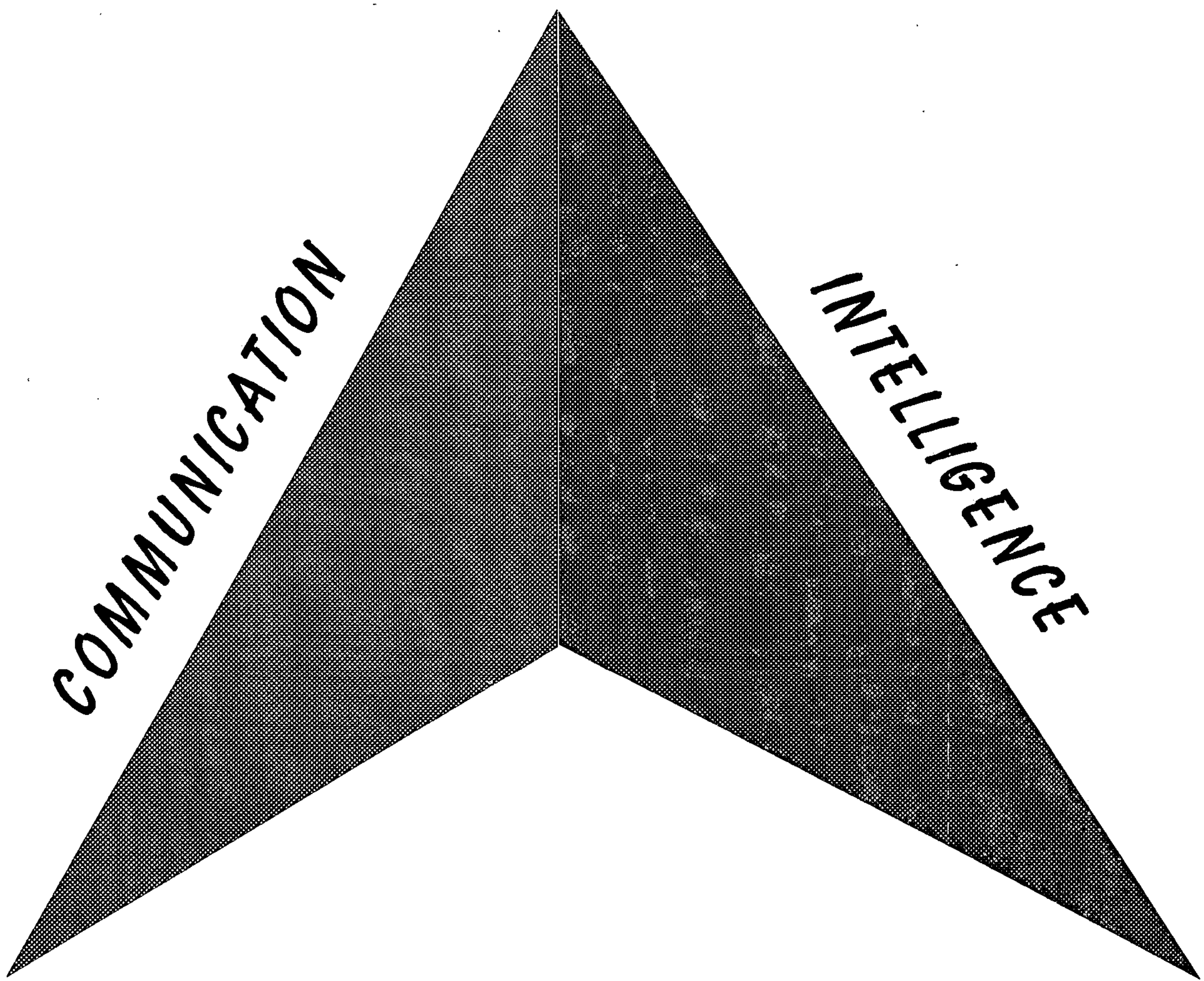
<table>
<tr><th></th><th>40-60's</th><th>70-80's</th><th>90's</th><th colspan="2">NEXT</th></tr>
<tr><td>PLAN</td><td>MASTER</td><td>SEGMENTED</td><td>SCHEDULED</td><td colspan="2">OPTIMIZE</td></tr>
<tr><td>TIMELINESS</td><td>NONE</td><td>EVENTUALLY</td><td>DELAYED</td><td colspan="2">IN TIME</td></tr>
<tr><td>EXECUTE</td><td>CENTRAL</td><td>KIOSK</td><td>DISTRIBUTED</td><td>USER</td><td>SERVICE PROVIDER</td></tr>
<tr><td>I T</td><td>BATCH</td><td>MAINFRAME ➤ PC</td><td>CLIENT / SERVER</td><td>MOBILE NODE</td><td>COMMERCIAL</td></tr>
<tr><td>COMMUNICATION</td><td>WIRED</td><td>WIRELESS VOICE</td><td>PRIVATE & COMMERCIAL WIRELESS DATA</td><td>PRIVATE WIRELESS DATA</td><td>COMMERCIAL WIRELESS DATA</td></tr>
</table>

TRAIN CONTROL PROJECT STATUS

	Source of TRAIN AUTHORITY	Display of TRAIN AUTHORITY	SOURCE OF VITAL	BLOCK	PRIME COMMUNICATION PATHS	TRAIN POSITIONING
UP's PTS	track circuits and office dispatch software	cab & signal system	track circuits	fixed	mobile ↔ central	GPS / Ded/ Inertia / GIS
UP's PTC	dispatch office software	cab	LOCOMOTIVE AND DISPATCH OFFICE SOFTWARE	moving	**MOBILE ↔ CENTRAL**	GPS / Ded/ Inertia / GIS
I T C S	currently signal system	cab	track circuits	improved fixed block	wayside ↔ mobile; wayside ↔ wayside	GPS / Ded / GIS
Transits' CBTC	on-board or wayside software	cab	LOCOMOTIVE AND/OR WAYSIDE SOFTWARE	moving	**WAYSIDE ↔ MOBILE WAYSIDE ↔ WAYSIDE**	various combinations
I DOT	on-board dispatch software	cab	track circuits	moving	mobile ↔ central	unknown, possibly markers / GPS / Ded
CONRAIL PROPOSAL	????????	????????	??			?????????

NOTE: Multiple use of a word in different blocks does not necessarily indicate interoperability

PTS = Positive Train Separation (enforcement)
PTC = Positive Train Control (moving block)
ITCS = Incremental Train Control System (enforcement with "intelligent" fixed block) in Michigan
CBTC = Communications Based Train Control - vital locomotive/wayside train control being pursued by transits
IDOT = Illinois Department of Transportation's conceptual program for moving block



IT ❖ COMMUNICATION PLATFORM

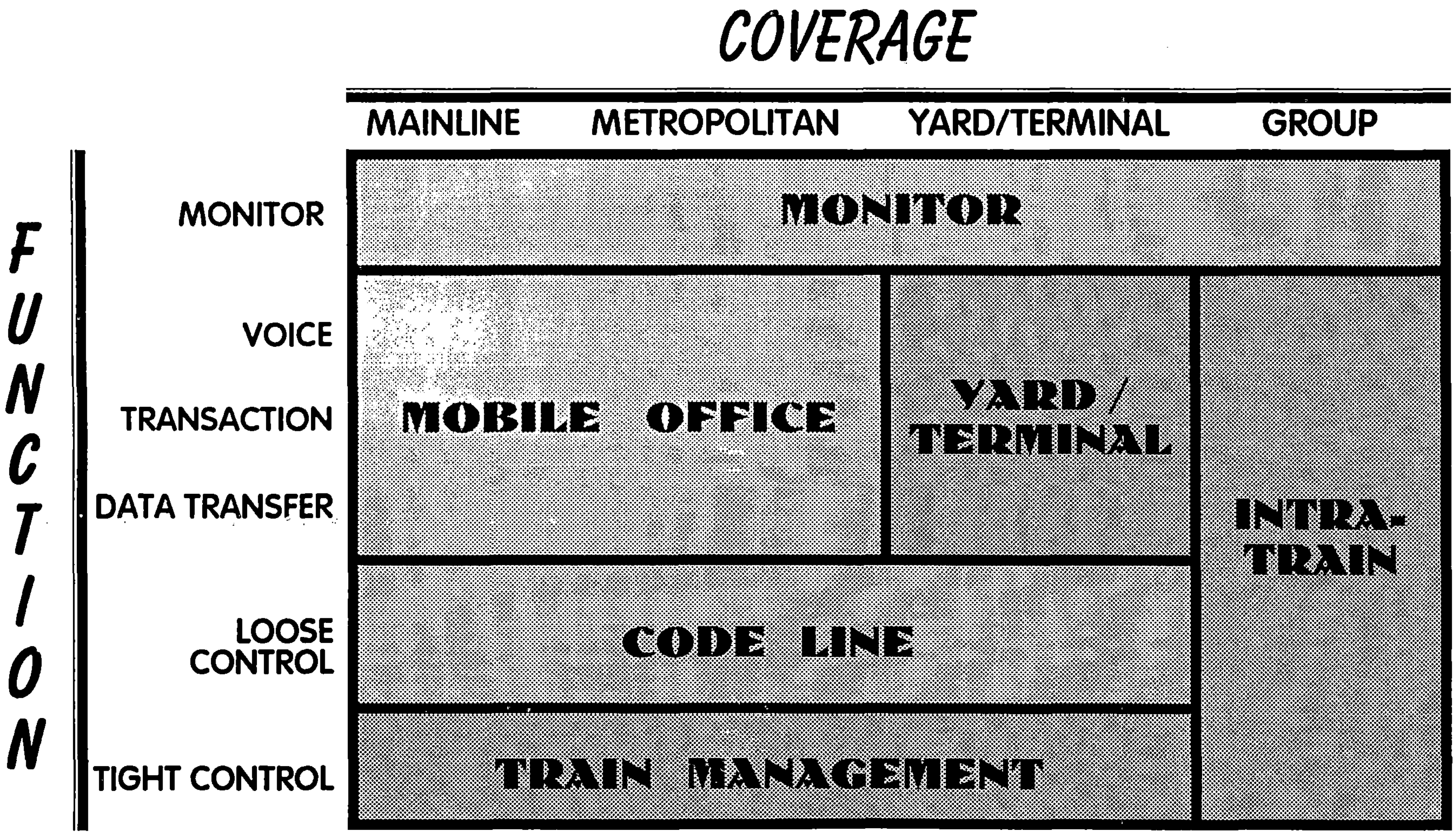
RAILROAD COVERAGE / FUNCTIONS

COVERAGE	FUNCTION
	MONITOR
MAINLINE	DATA TRANSFER
METROPOLITAN	TRANSACTION
YARD / TERMINAL	VOICE
GROUP	LOOSE CONTROL
	TIGHT CONTROL

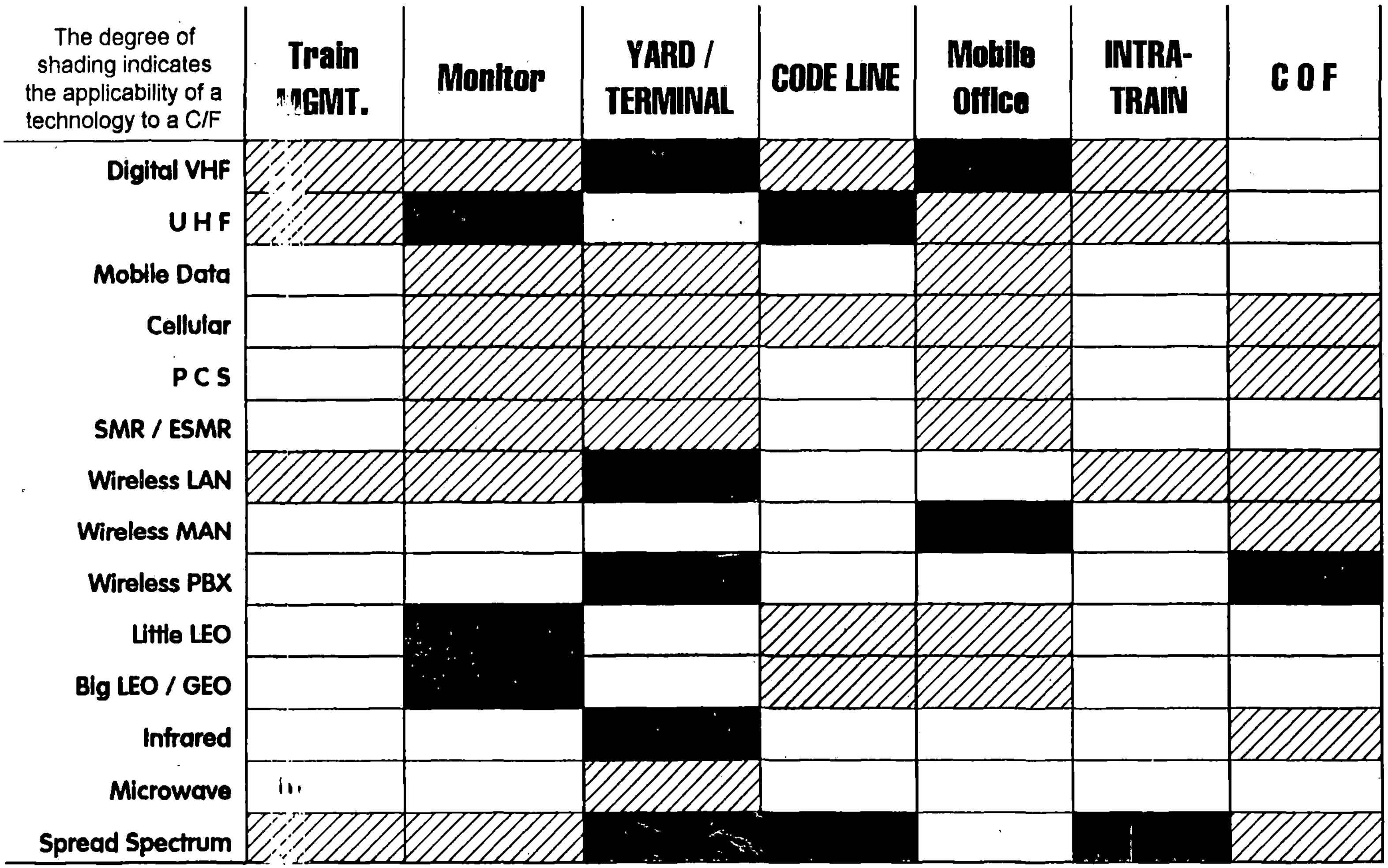
COVERAGE

FUNCTION	MAIN	METROPOLITAN	TERMINAL	GROUP
MONITOR	1	2	3	4
DATA TRANSFER	5	6	7	8
TRANSACTION	9	10	11	12
VOICE	13	14	15	16
SCADA	17	18	19	20
PROCESS CONTROL	21	22	23	24

WIRELESS CORRIDORS



TECHNOLOGIES BY COVERAGE / FUNCTION



There are two key points to this chart:

1. No one technology can adequately serve each C/F, and hence
2. A blending of technologies will be required.

ISSUES - THREE TECHNOLOGY PLATFOMS

POSITIONING

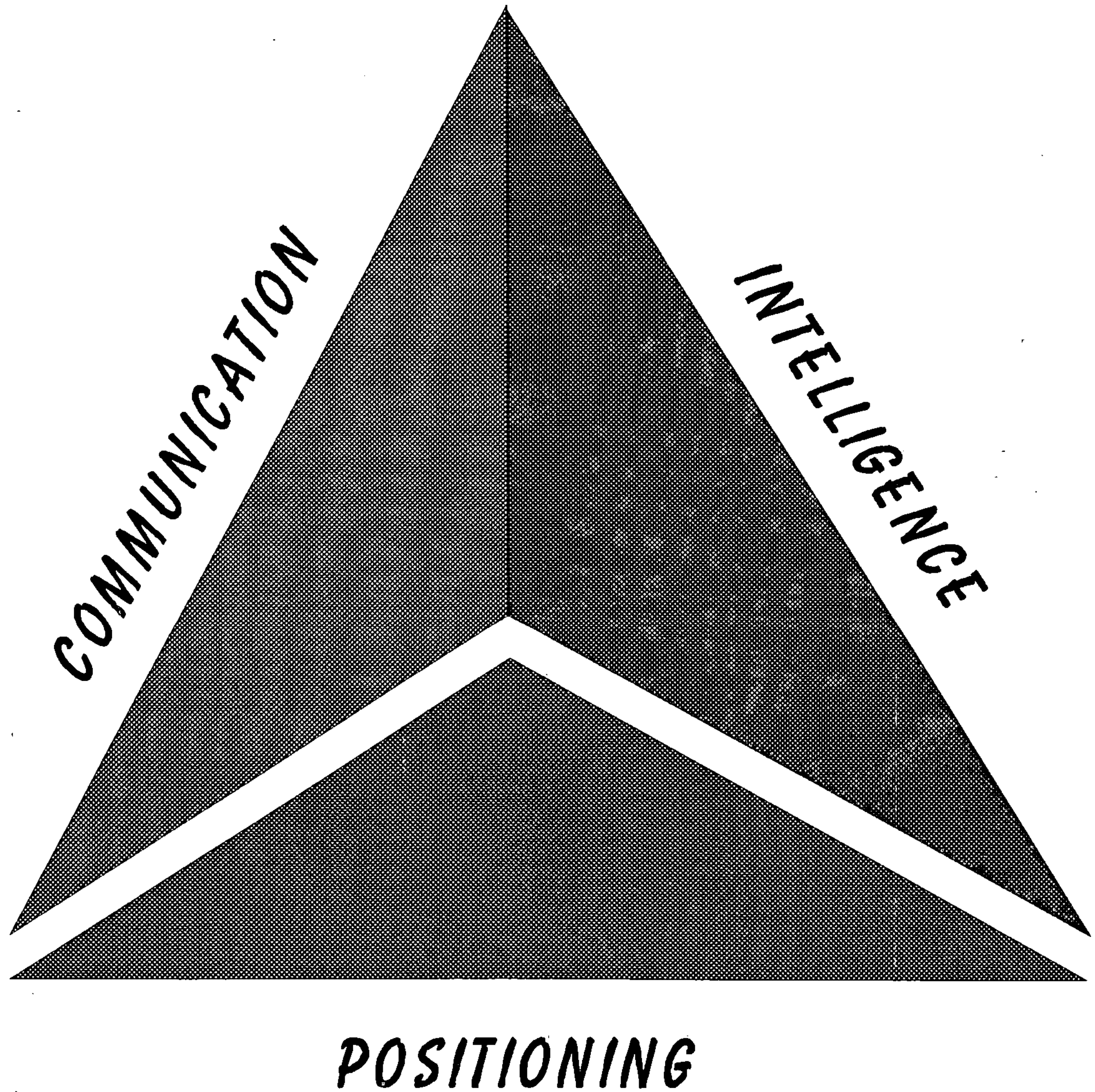
levels of precision
G P S
G I S
other

IT / LOGIC

control flow essence
distributed
hierarchial
wayside
mobile

COMMUNICATIONS

VHF refarming
900 private
commercial blends
conduits


COMMUNICATION
INTELLIGENCE
POSITIONING

RAILROADS HAVE ONE

DIMENSION OPERATIONS

USING ASSETS WITH

2 & 3 DIMENSIONS

DEMAND

understanding the business processes and identifying the need for positioning data as to:

- COVERAGE
- TIMELINESS
- ACCURACY
- ARCHITECTURE

FUNCTION

ASSETS	SPEED	VITAL	EFFICIENCY (ASSET USAGE)	ADMIN (INVENTORY)
TRACK / TRAIN				
LOCOMOTIVE				
ROLLING STOCK				
TRAIN CREWS				
MAINTENANCE CREWS				
FACILITIES				

FUNCTION

WHERE USED	SPEED	VITAL	EFFICIENCY (ASSET USAGE)	ADMIN INVENTORY)
ON TRACK				
MOBILE				
WAYSIDE				
OFFICE				
OFF PROPERTY				

GPS THE TECHNOLOGY

GIS THE PLATFORM

MINIMAL UNDERSTANDING / PURSUIT OF GIS CONCEPTS

LOW AVAILABILITY OF QUALIFIED PERSONNEL

MINIMAL APPRECIATION OF GRAPHICAL REPRESENTATION

WIDE VARIANCE IN DEGREE OF DATA ACCURACY

NO STRATEGIC PLAN ACROSS DEPARTMENTAL BOUNDARIES

GOOD DATA MAY NOT BE READILY AVAILABLE OR AFFORDABLE

Information Architecture

WHO

CREATES
USES
CHANGES
DELETES

POSITIONING INFORMATION

WHY IS POSITIONING INFORMATION REQUIRED?

WHAT HAS BEEN AVAILABLE AND WHAT IS REALLY REQUIRED AS TO:

* TIMELINESS * ACCURACY * COVERAGE

WHAT BENEFITS CAN BE REALIZED WITH THE AVAILABILITY OF IMPROVED INFORMATION?

WHO ELSE NEEDS THE SAME INFORMATION?

Condition Monitoring and Maintenance Planning

GPS and GIS Applications

Presented by Kevin Kesler
ENSCO, Inc.
November 14-15, 1996

Objective:

- To present a vision of the future for the use of GIS and GPS in railroad field inspections and maintenance

- To describe some of examples of the current or near term applications of GPS and GIS and the benefits of their use

- To suggest an approach for the implementation of GPS and GIS technology for Railroads which contemplating their use

Benefits of GPS, GIS and remote data comunications for railroad field maintenance and inspection

- Reduce track occupancy time required for inspection and maintenance

- Provide positive link between inspection and maintenance operations

- Enable central database for improved management of inspection and maintenance operations

- Improve the efficiency and effectiveness of automated track inspection operations

Examples of the Application of GPS, GIS and Remote data communcations for Railroad Field Inspection and Maintenance - Current and Near Term

- FRA T-10 Automated Track Inspection Program Differential GPS

- FRA Gage Restraint Measurement System Diferential GPS

- Amtrak and FRA Portable Ride Quality inspection systems with Differential GPS

- Amtrak 10002 Track Geometry Inspection System

- GIS for Rail Flaw Inspection Data Management and Inspection Planning/Tracking

- Conrail Remote Locomotive Monitoring System (Prototype)

- Electronic Recordkeeping for Track Inspection (BNSF Waiver)

Suggested Approach for Implementation-

1- Start with available GIS databases
   - ie- TIGER Files, BTS and FRA Databases

2- Identify specific applications

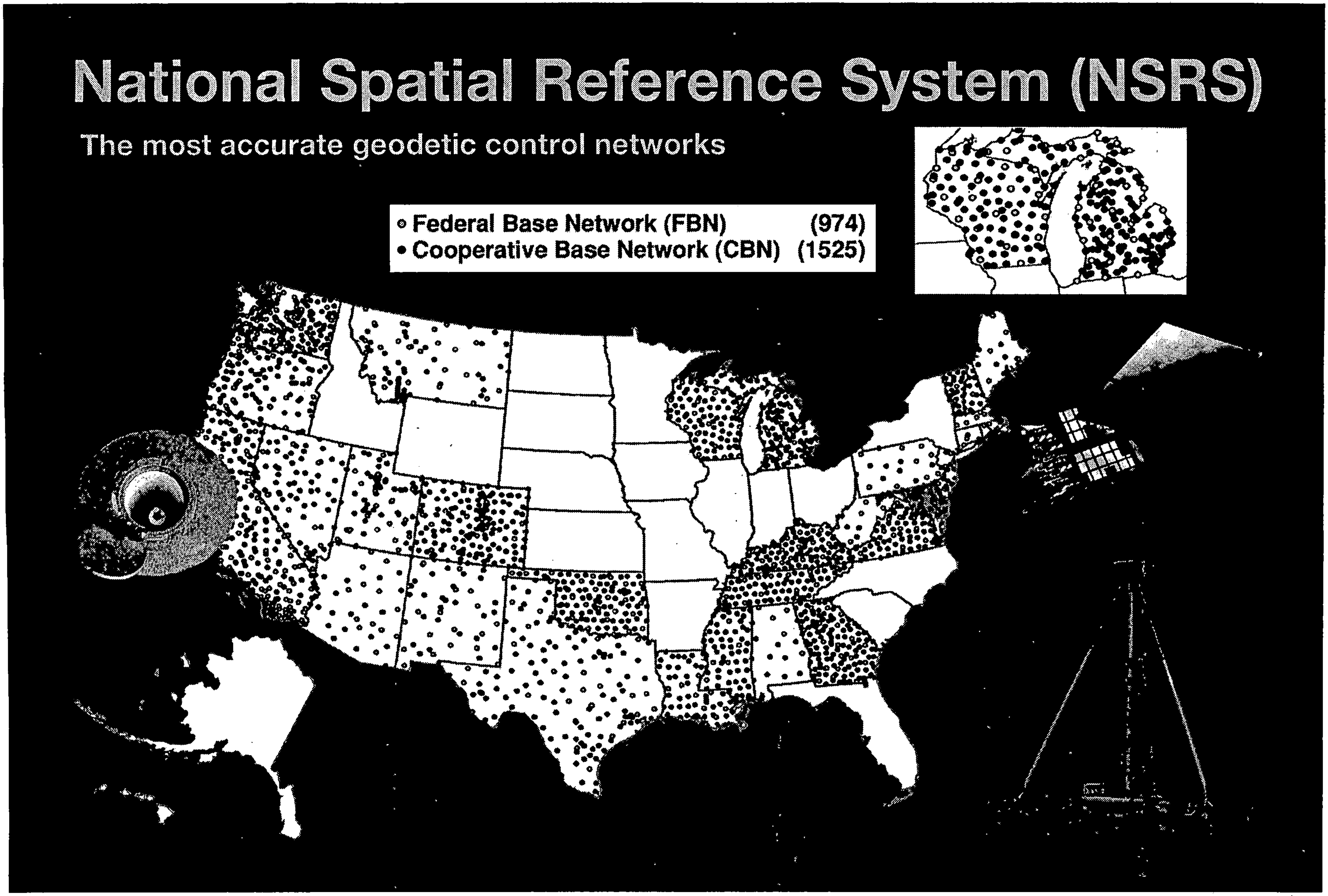
3- Determine minimum acceptable resolution and accuracy for desired application(s)
   - Greater accuracy means greater cost but not necessarily greater benefit...
   - Future improvements are always possible and cperhaps at lower cost

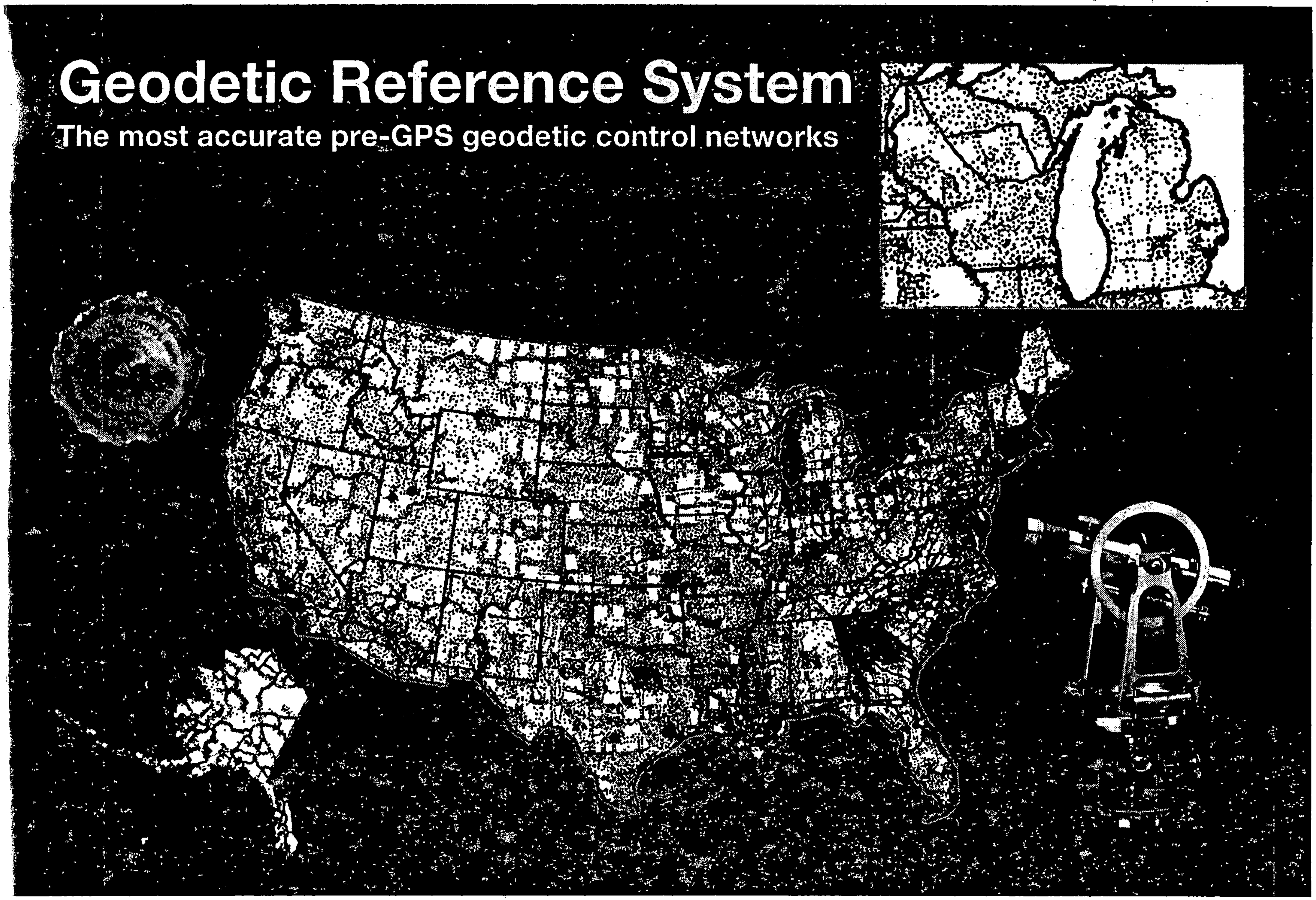
4- Use GPS (Differential if possible) systems during routine inspection operations to capture more precise and complete data and update databases

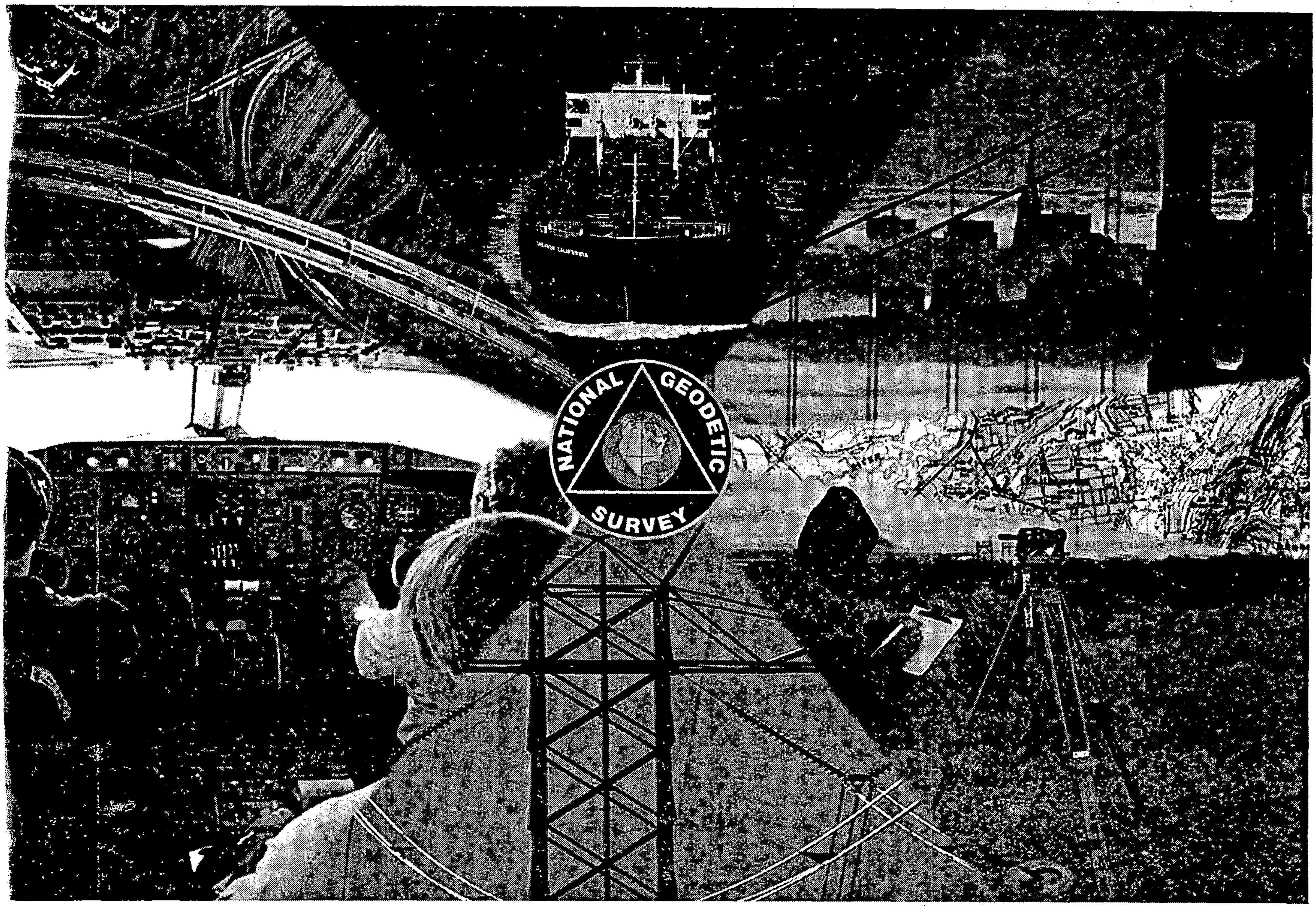
Suggested Approach for Implementation- (Cont'd)

5- Select a commercially available GIS to use as a base,
One that fits the needs of the applications.
In many ways GIS systems are like word processing software...
...There are many systems available...
...some with more power than others.
...Most will read other databases.

6- Avoid trying to 'do it all' in one bite.
Make one application successful and build from there.


National Spatial Reference System (NSRS)
The most accurate geodetic control networks
Federal Base Network (FBN) (974)
Cooperative Base Network (CBN) (1525)


Geodetic Reference System
The most accurate pre-GPS geodetic control networks

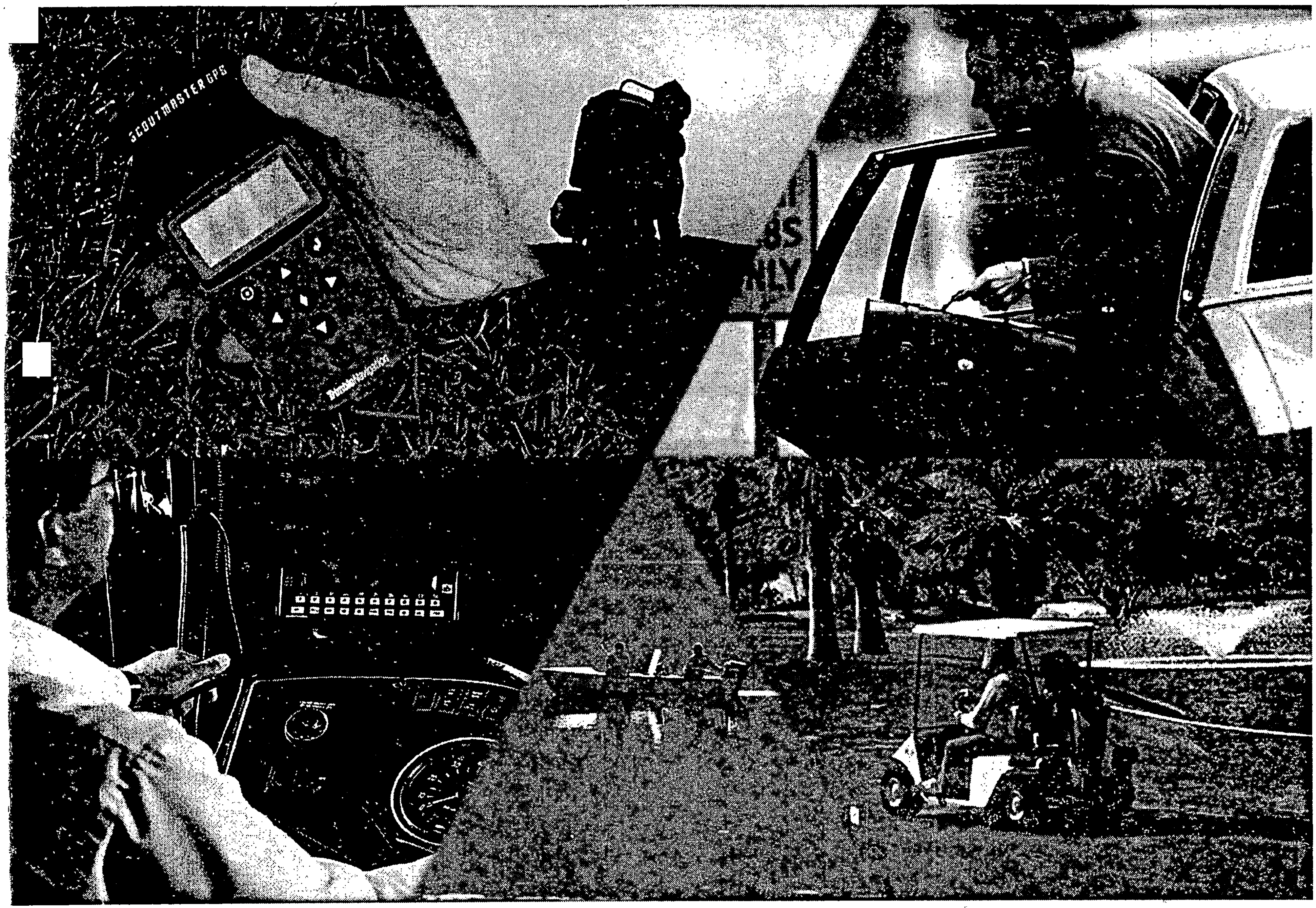

NATIONAL GEODETIC SURVEY

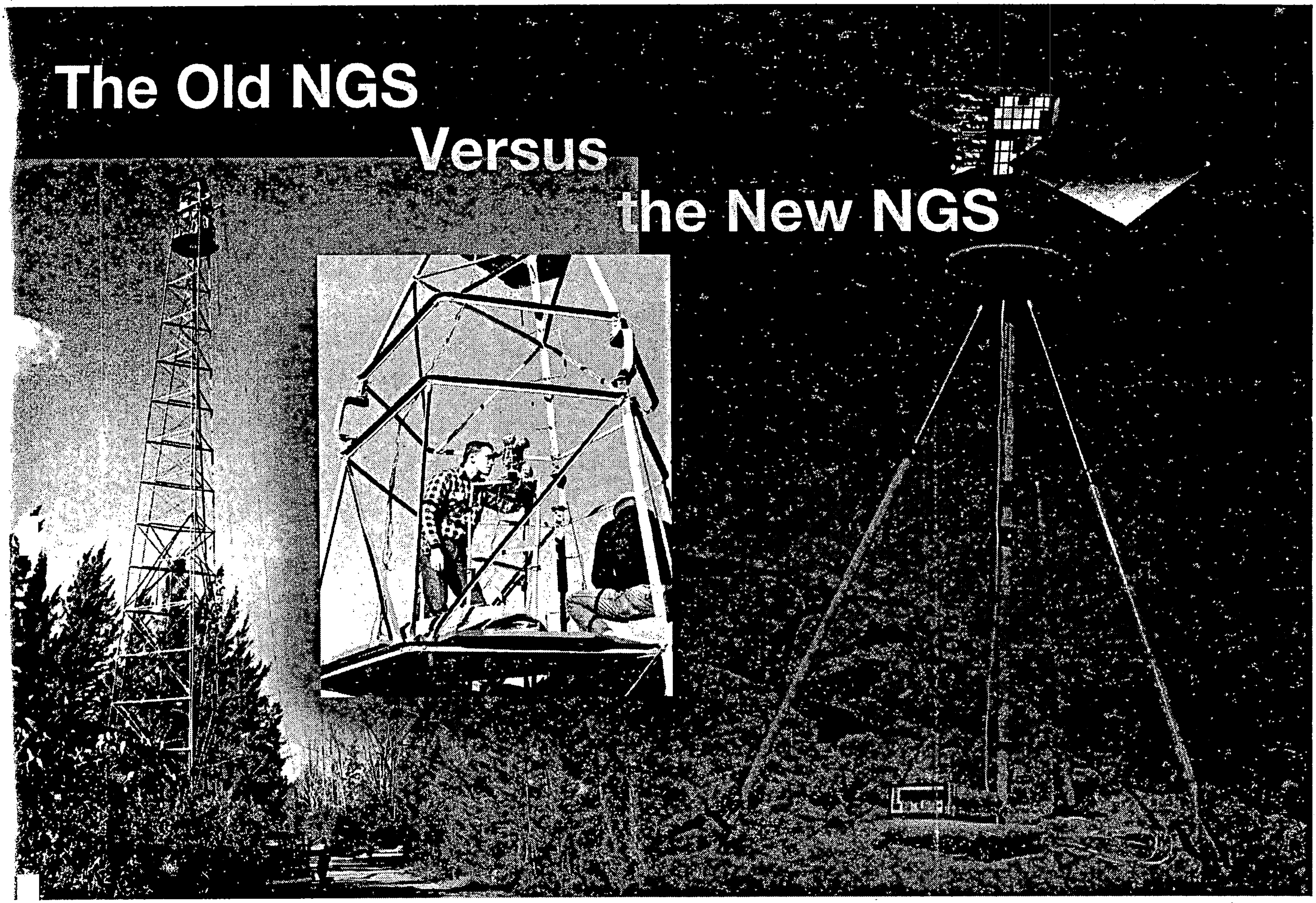
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

NOAA

U.S. DEPARTMENT OF COMMERCE

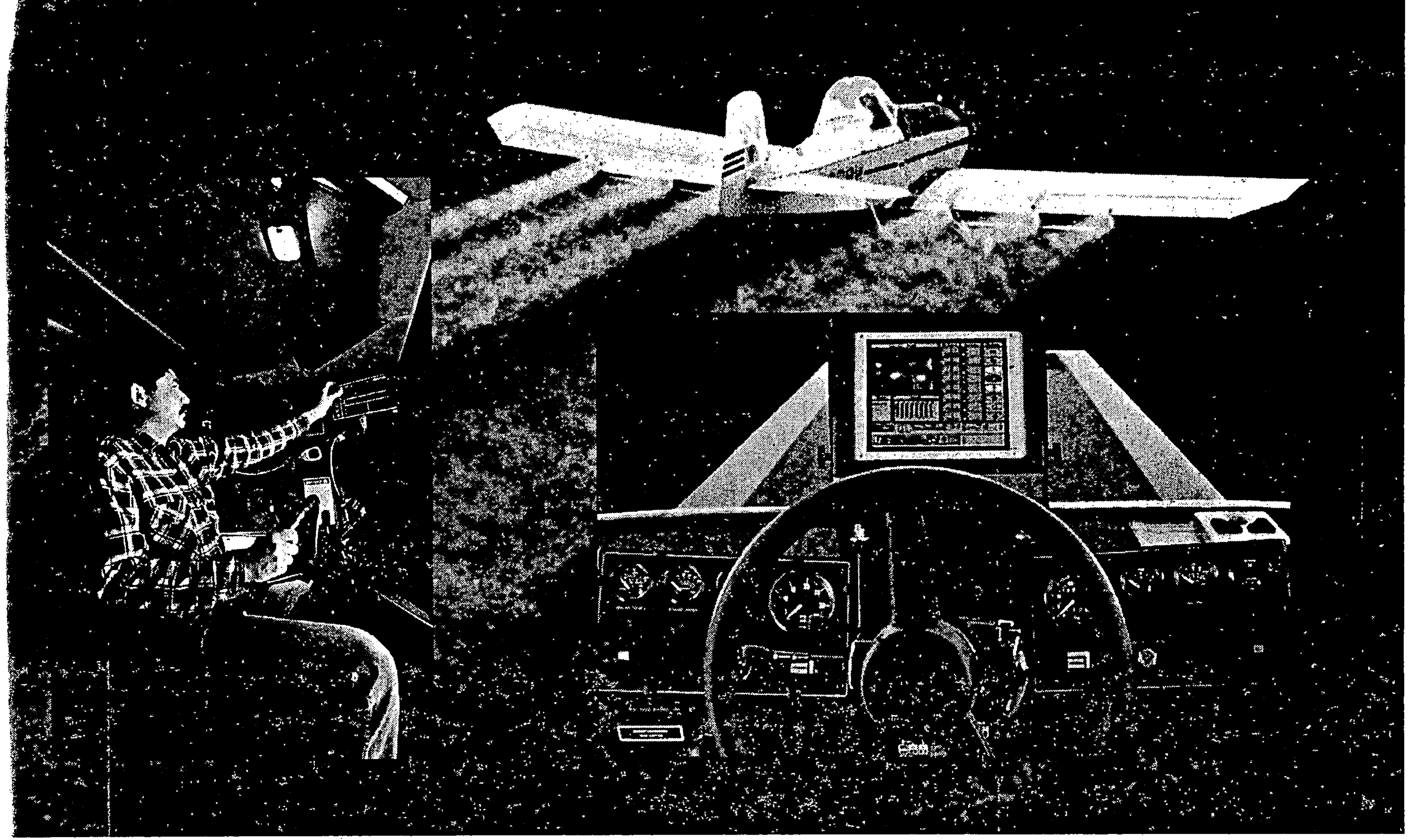
NATIONAL GEODETIC SURVEY


SCOUTMASTER GPS
Trimble Navigation

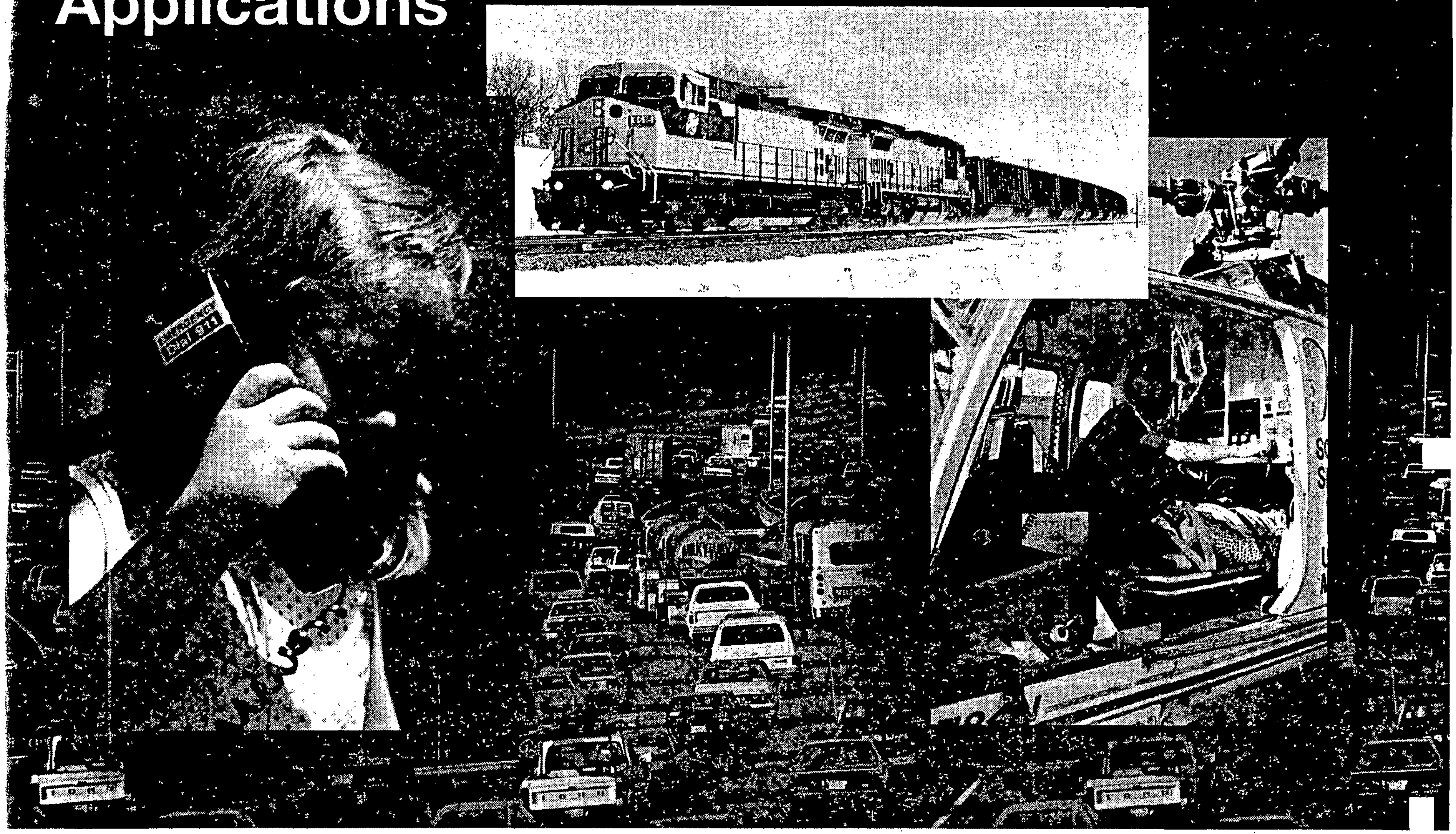


The Old NGS
Versus
the New NGS

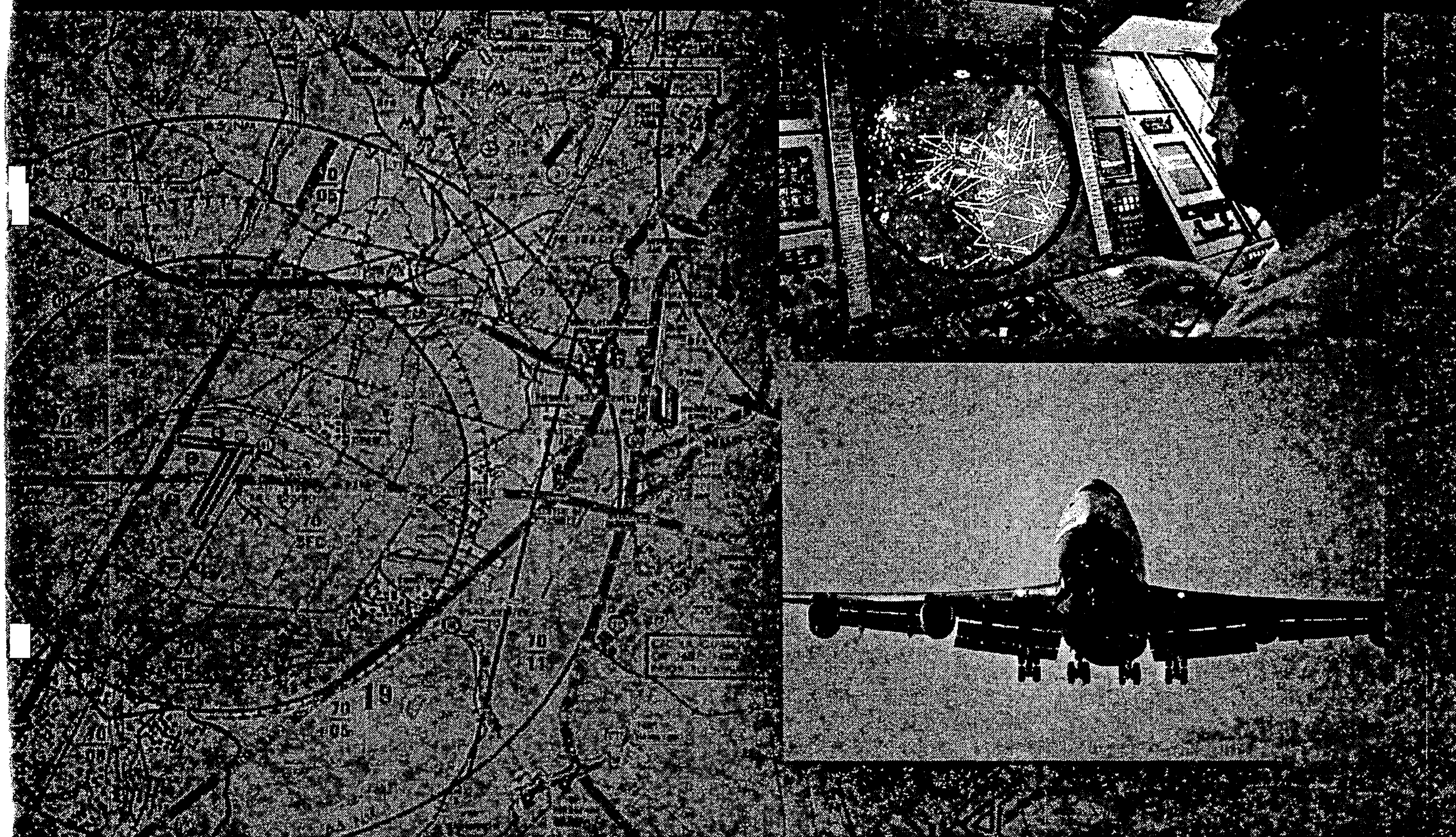
Agriculture



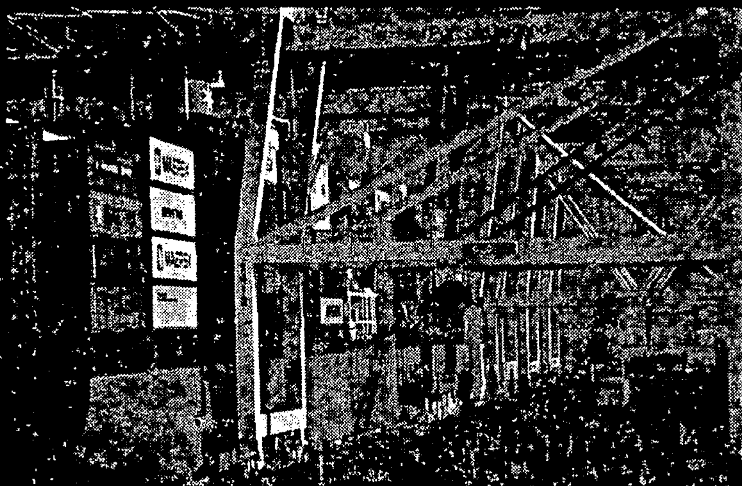
Land Transportation and Emergency Applications

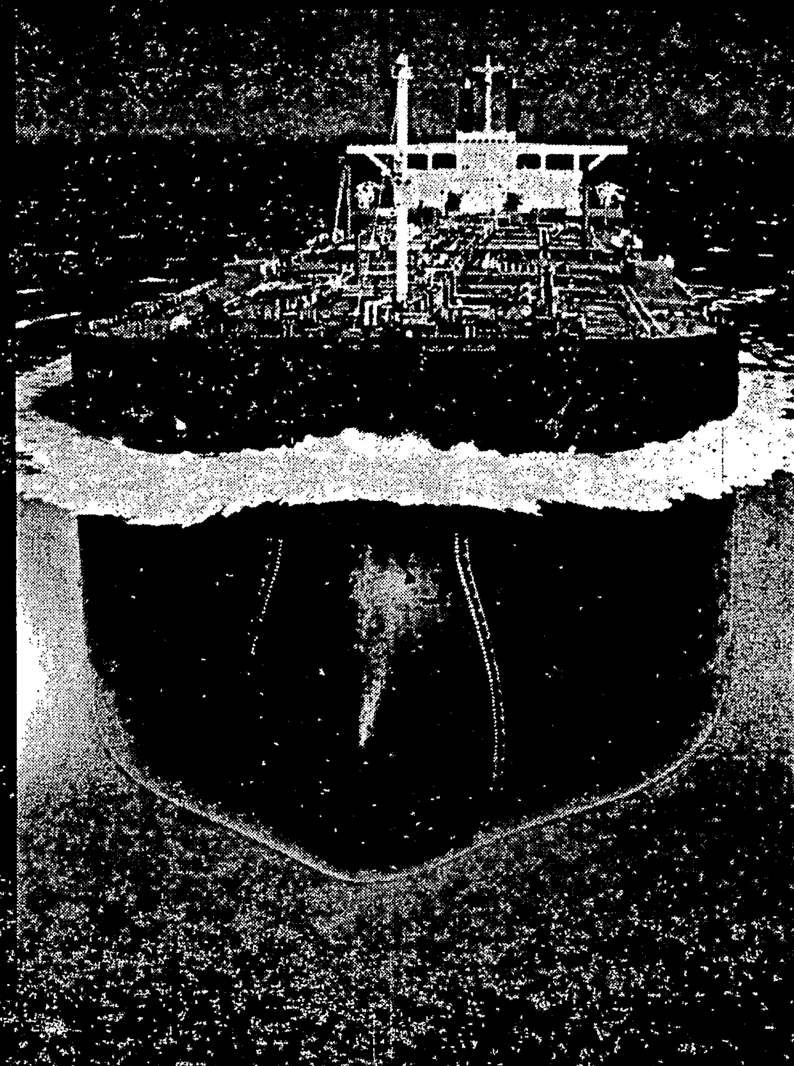


Aviation

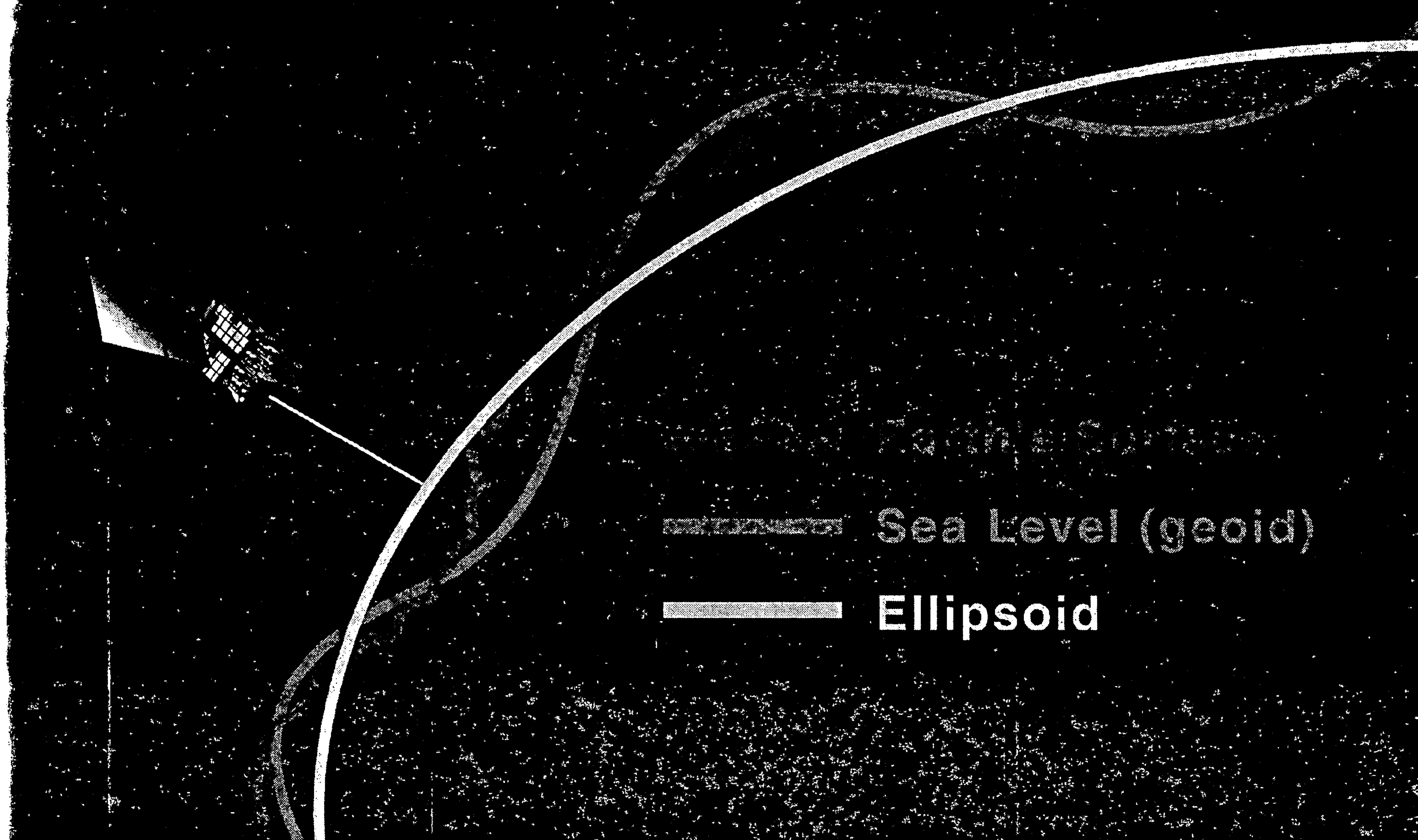


Maritime Applications

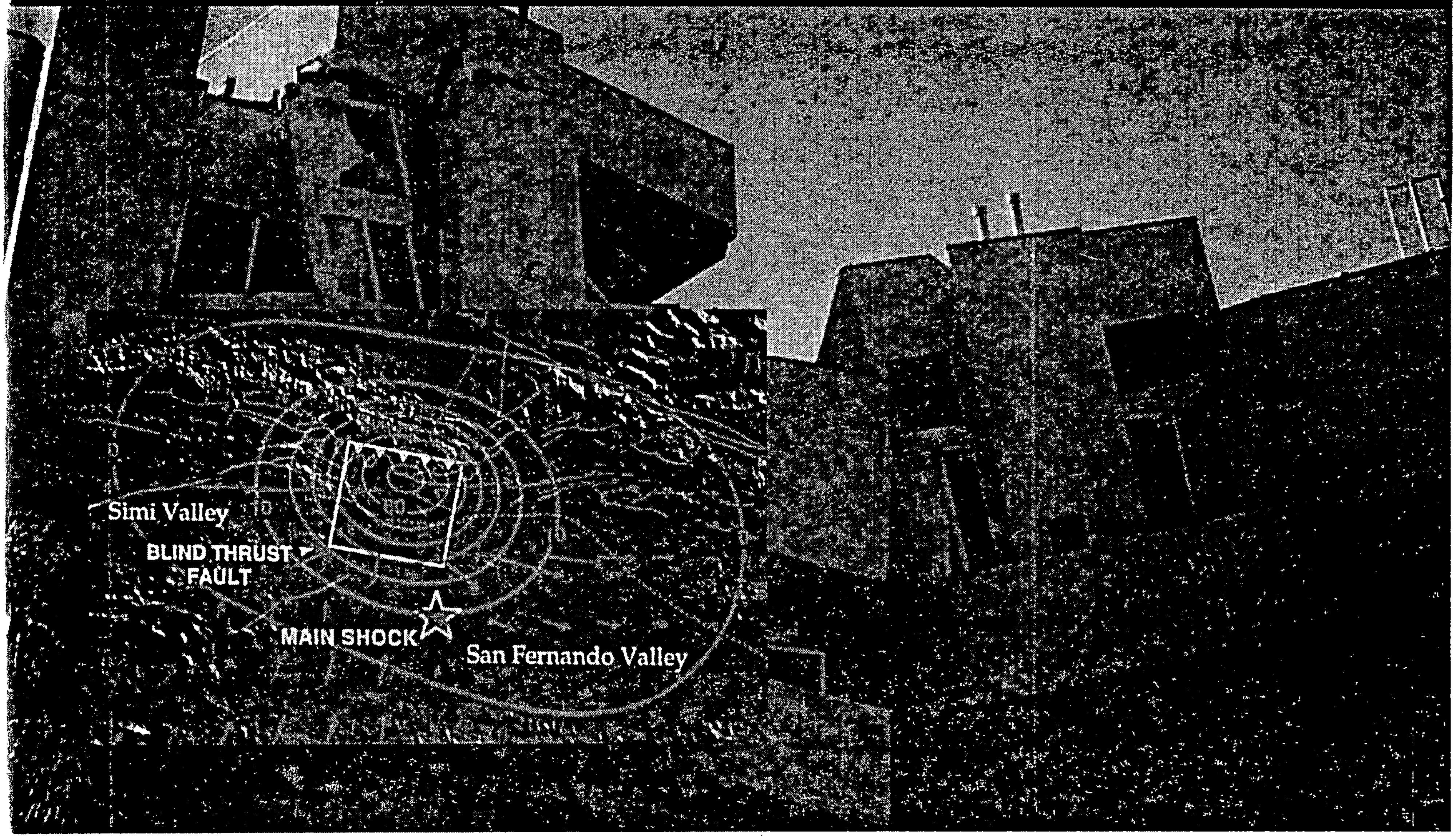




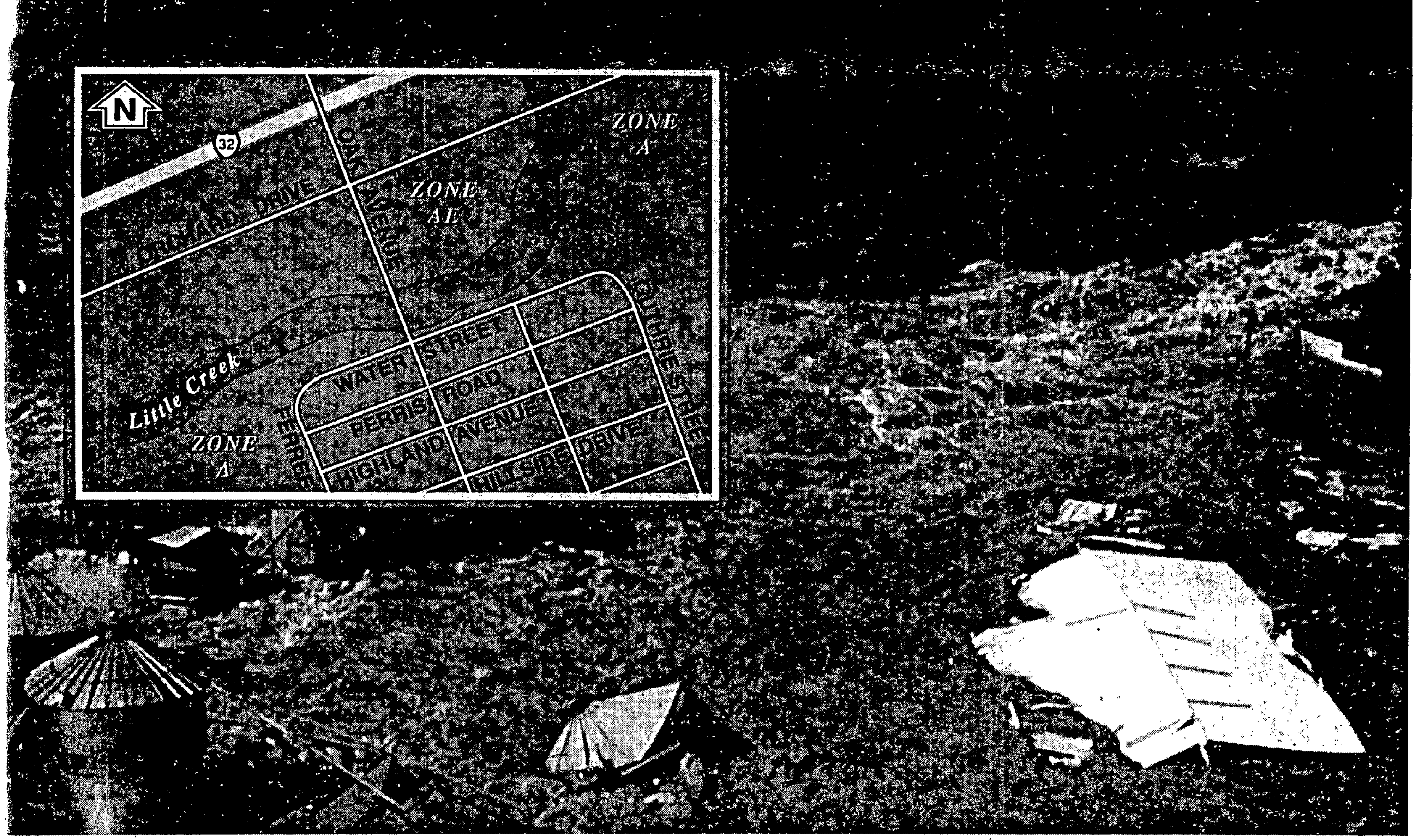
How geodesists view the world



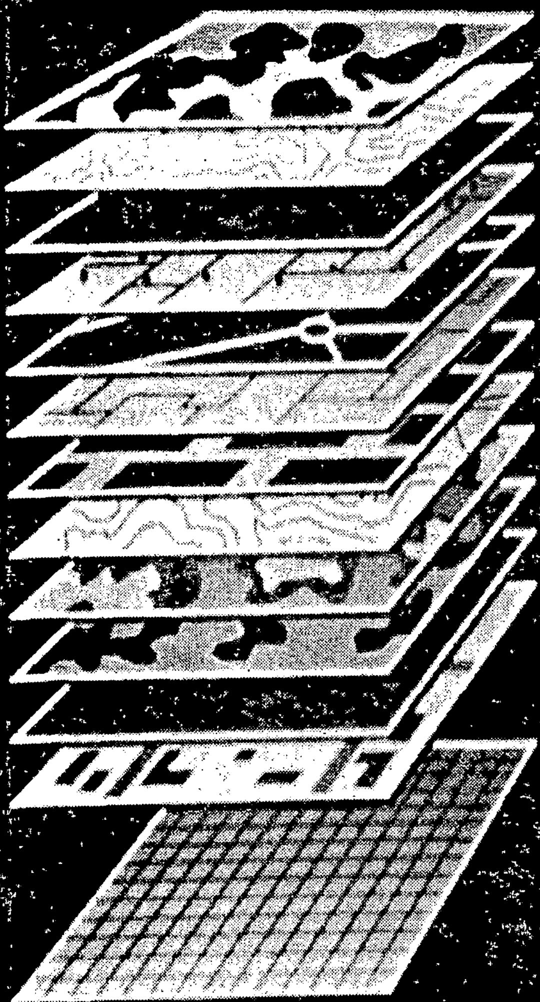
Geodynamic measurements



Flood Mitigation

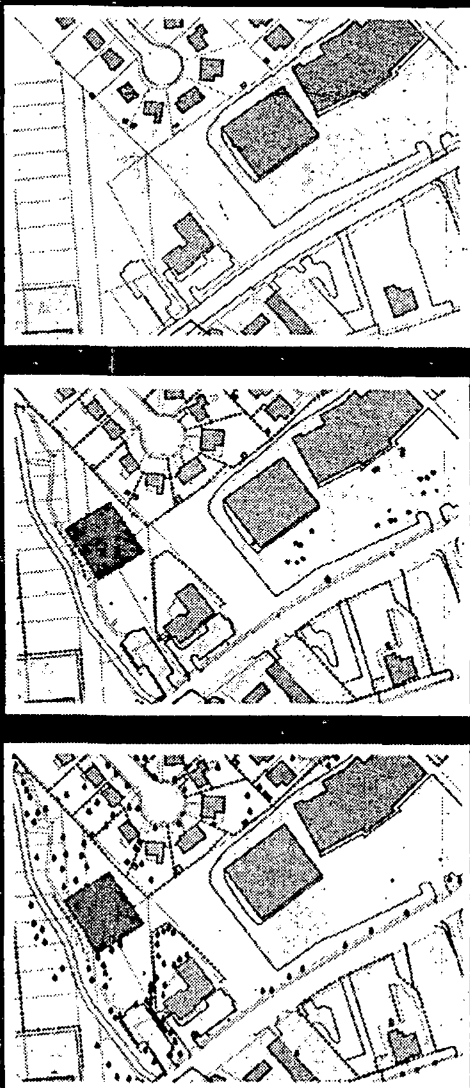


Geographic Information

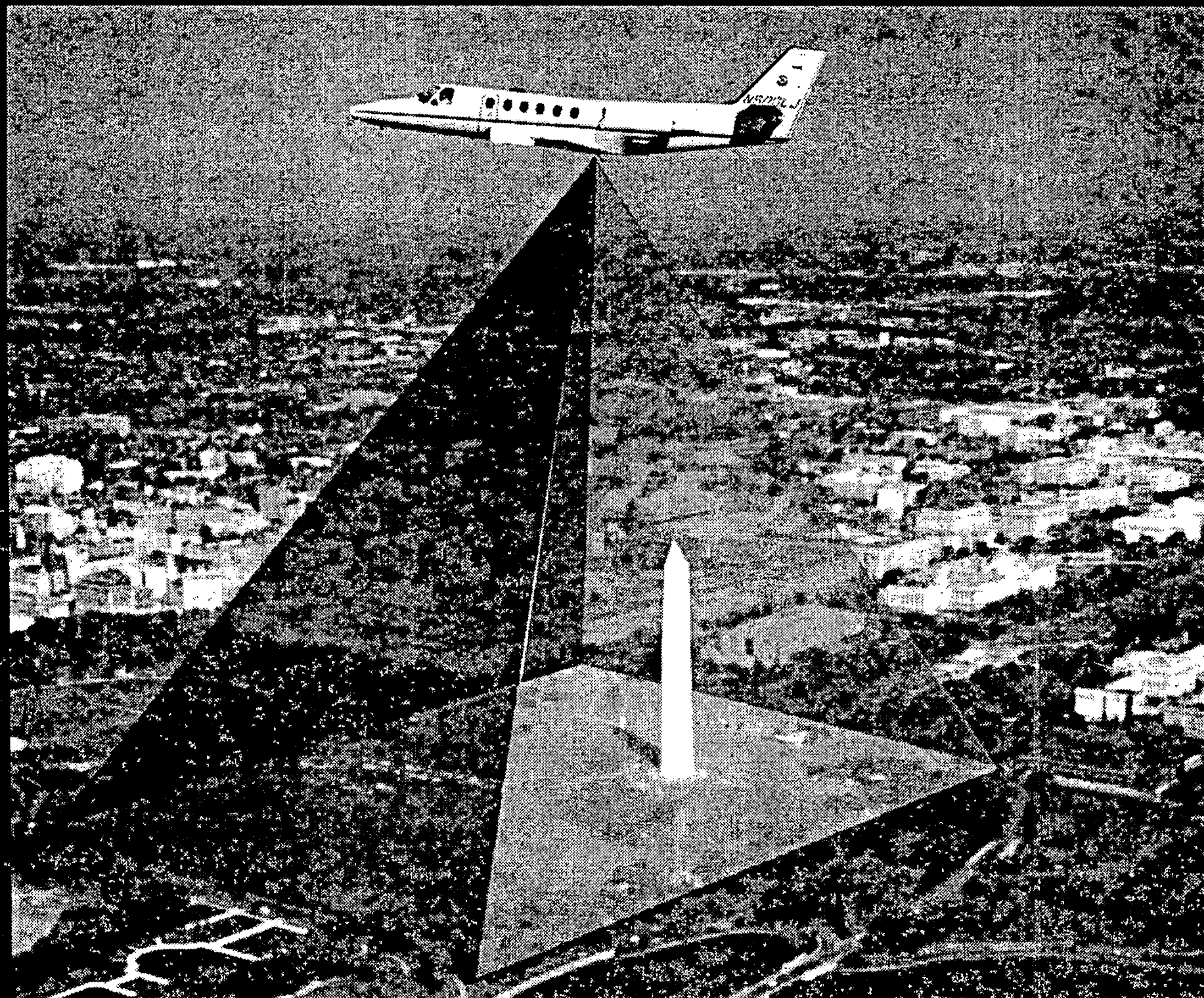


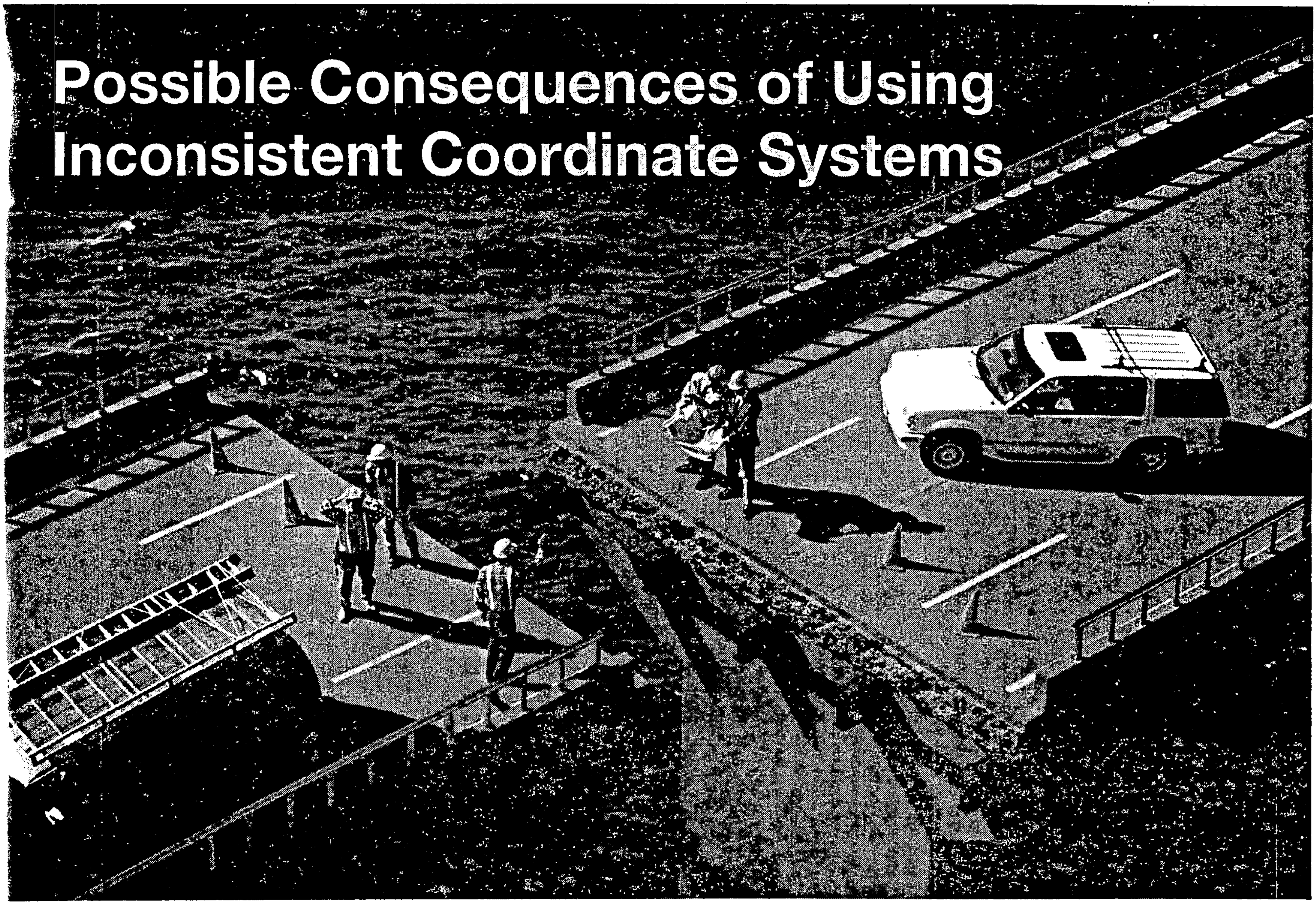
Geodetic Control
Topography
Soils
Hydrology
Land Use
Boundaries
Roads
Electrical Utilities
Sewerage
Water Utilities
Structures
Demographics

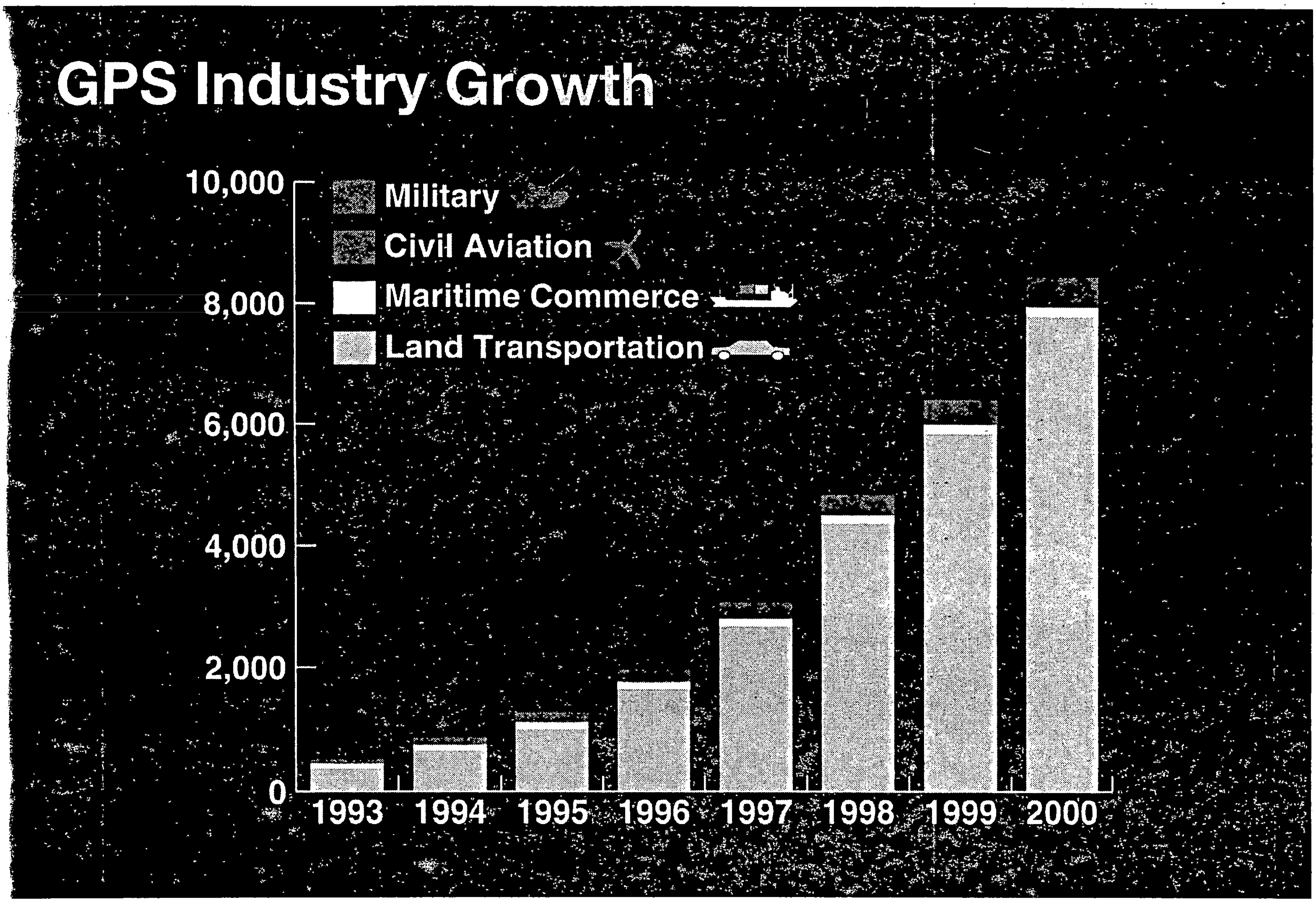
n Systems (GIS)

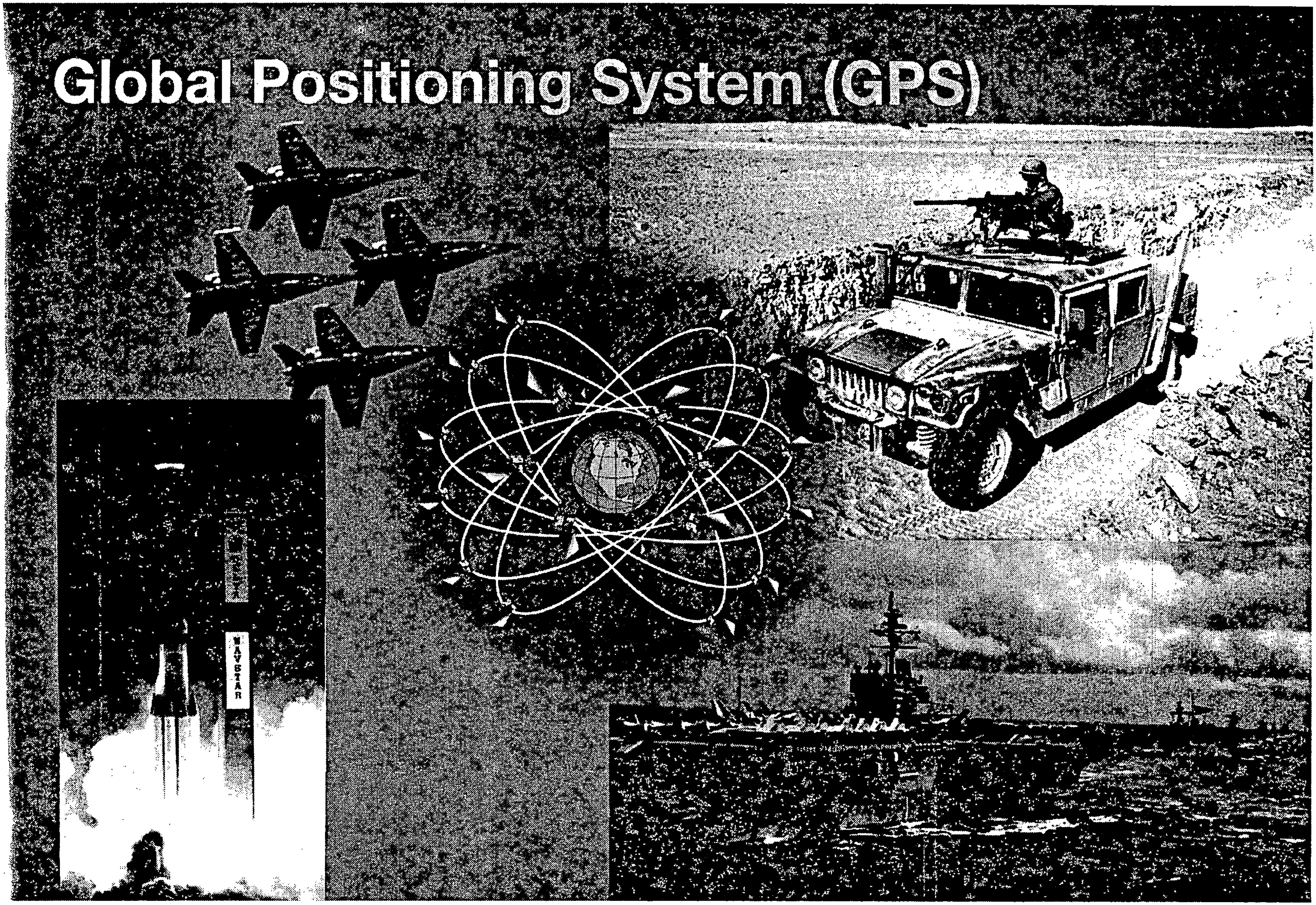


Photogrammetry



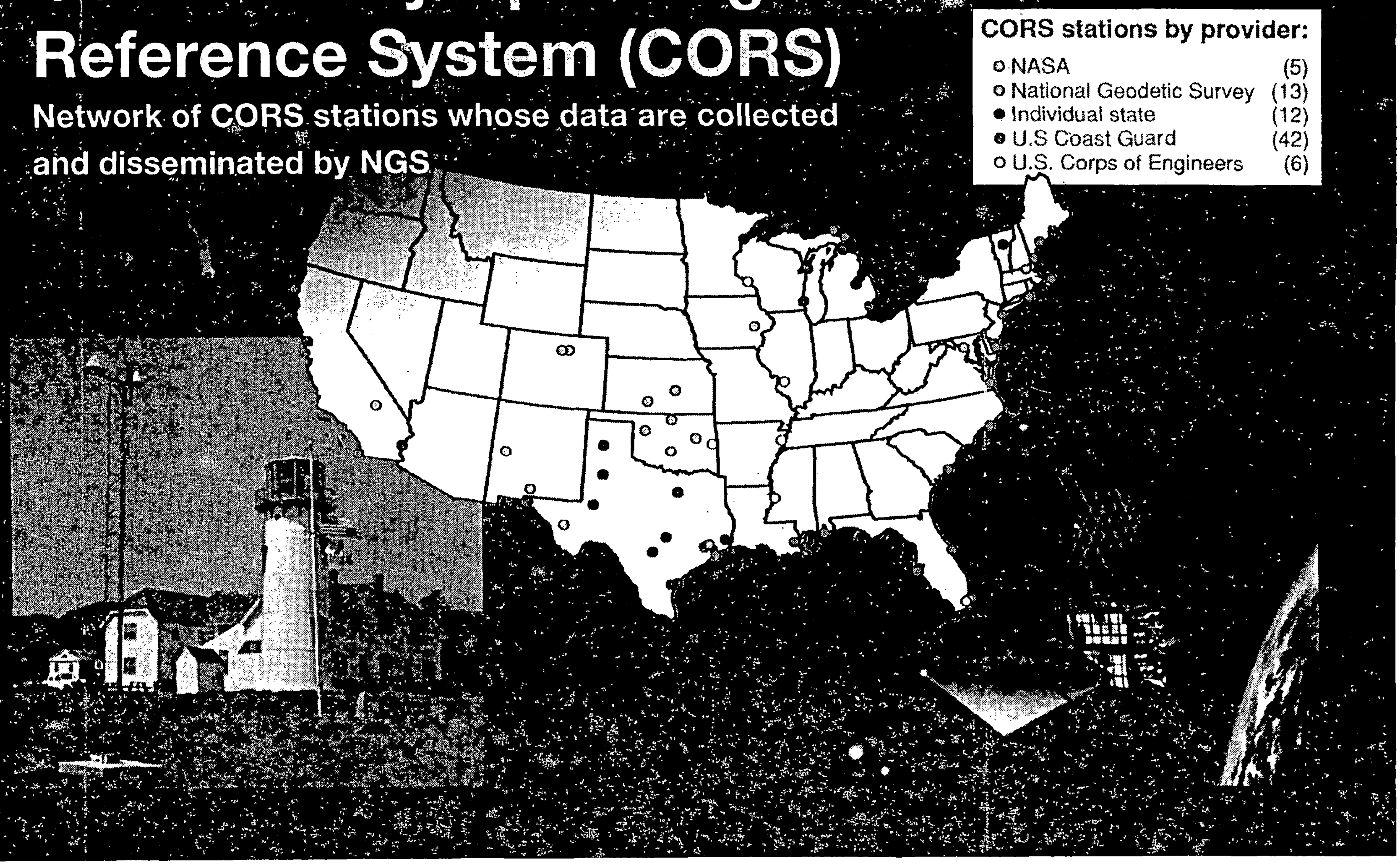

Possible Consequences of Using
Inconsistent Coordinate Systems


GPS Industry Growth
10,000
8,000
6,000
4,000
2,000
0
Military
Civil Aviation
Maritime Commerce
Land Transportation
1993
1994
1995
1996
1997
1998
1999
2000


Global Positioning System (GPS)
NAVSTAR

Continuously Operating Reference System (CORS)

Network of CORS stations whose data are collected and disseminated by NGS



GPS

Continuing an Industry / Government Policy Success

The International Challenge

F. Michael Swiek
Executive Director
United States GPS Industry Council

UNITED STATES GLOBAL POSITIONING SYSTEM INDUSTRY COUNCIL

★★ USGIC ★★

Suite 535
1100 Connecticut Avenue, NW
Washington, DC 20036

Tel.: 202-296-1653 FAX : 202-862-3929

USGIC MEMBERS

-- Are original technology innovators

-- Account for ~60-75% of US production

Ashtech
Honeywell
Lockheed-Martin
Magellan
Motorola
Rockwell
Trimble

MISSION

-- To be an information resource to government

-- Promote sound policies for the development of commercial markets and civilian applications while preserving military advantages of GPS

UNITED STATES GLOBAL POSITIONING SYSTEM INDUSTRY COUNCIL
** USGIC **

GPS APPLICATIONS

DID YOU KNOW ?

GPS is a technology whose applications will be as ubiquitous as the telephone and as revolutionary as the personal computer. GPS has the potential to be employed in almost every facet of everyday life.

GPS MARKETS

Annual Sales of GPS Receiver Equipment

1989 - **$ 40 MILLION**

1993 - **$460 MILLION**

2000 - **$ 5-6 BILLION**

USGIC

GPS Market Projections — Worldwide

(Sales in $ millions)

	1993	1994	1995	1996	1997	1998	1999	2000
Car Navigation	100	180	310	600	1100	2000	2500	3000
Consumer/Cellular	45	100	180	324	580	1000	1500	2250
Tracking	30	75	112	170	250	375	560	850
OEM	60	110	140	180	220	275	340	425
Survey & Mapping	100	145	201	280	364	455	546	630
GIS	25	35	50	90	160	270	410	650
Aviation	40	62	93	130	180	240	300	375
Marine	80	100	110	120	130	140	150	160
Military	30	60	70	80	90	100	110	130
	510	*867*	*1266*	*1974*	*3074*	*4855*	*6416*	*8470*

UNITED STATES GLOBAL POSITIONING SYSTEM INDUSTRY COUNCIL

** USGIC **

GPS MARKETS

The rate of technical change in the industry is ferocious. Product cycles of 12-18 months are typical.

GPS receiver products are rapidly becoming "commodity" items with costs dropping at 30% per year. Hand held GPS receivers are now available for less than $500. Costs for OEM modules for integration into other systems are now below $300 per unit.

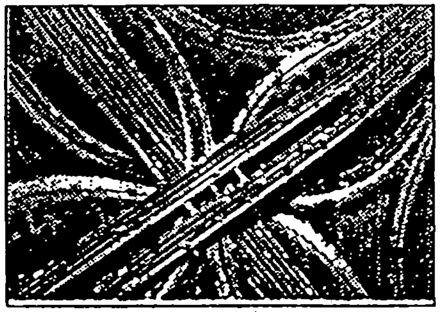
$350

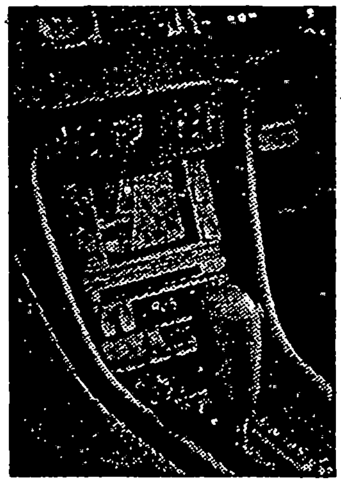
$150

AUTOMOTIVE/OEM MARKET

Vehicle Navigation End Users

Over 300 Million Vehicles Worldwide





- Integrated systems providing navigational information in the form of graphics and text on a small on-board computer screen

- Precise location combined with embedded databases to provide optimal route planning

RECREATION MARKET

Market Potential

Key Outdoor Recreational Activities
U.S. Adults

Activity	Participation
Freshwater Fishing	25,397,000
Camping	20,166,000
Hunting	13,488,000
Hiking	12,860,000
Bicycling	12,731,000
Saltwater Fishing	8,194,000
Downhill Skiing	7,181,000
Cross Country Skiing	7,491,000
Motorcycle Trail	3,376,000
Backpacking	3,016,000
Autorallying	1,800,000

Source: Simmons Market Research.

UNITED STATES GLOBAL POSITIONING SYSTEM INDUSTRY COUNCIL

** USGIC **

GPS APPLICATIONS

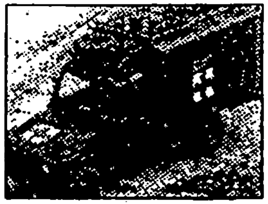
Agriculture:

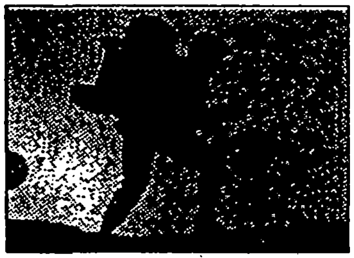
DID YOU KNOW ?

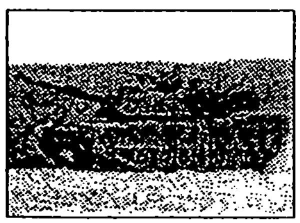
Allow farmers to apply precisely monitored and measures amounts of fertilizer or pesticide based on a detailed analysis of soil types and the exact location of each area to be treated.

MILITARY MARKET

End Users







Over 16 Million Armed Forces Personnel

- All branches of the armed forces worldwide
- Specialized receivers for ground combat forces
  - Location, coordination and tracking of troop movement and equipment
  - Time synchronization
  - Forward observation
  - Vehicle navigation, medevac, search and rescue
  - Artillery targeting, fire direction and support

CIVIL USES OF GPS

AVIATION

- Precision and non-precision all-weather approaches (WAAS)
- Direct routing for aircraft fuel savings
- Local, national and international enroute navigation
- Closer aircraft separation standards for more efficient air traffic management
- Airport surface traffic management
- Monitoring of wing deflection in flight
- Wind shear detection
- Precise airfield and landing aid to all airports, regardless of development
- Seamless (global) air space management
- Less expensive/more accurate avionics
- Inflight monitoring of position/location
- Enhanced Loran C in-flight navigation
- Search and locations of downed aircraft

COMMUNICATIONS

- Precise timing for interlacing messages
- Wide-area synchronization of highspeed networks
- Validation of information transmission
- Tagging of information for time-delayed transfer to data ports
- Network management and control
- Mobile use position determination for rapid linking to PCS
- Stochastic networking among cooperative mobile platforms
- Differentiation of wireless mode: cordless, cellular, satellite, etc.
- Personal navigation and reporting
- US/Global Information Infrastructure
- National Spatial Data Infrastructure

ENVIRONMENTAL PROTECTION

- Ground mapping of ecosystems
- Hazardous waste site investigation
- Mapping of sub-surface contamination
- Oil spill tracking and cleanup
- Precise location of stored hazardous materials
- Sudden alert for stored hazardous material moved without consent
- Monitoring of natural gas pipelines

FORESTRY AND AGRICULTURE

- Forest area and timber estimates
- Identifying specie habitats
- Fire perimeters
- Water resources
- Precise plowing, planting and fertilizing
- Unmanned (robotic) harvesting
- Precision crop dusting by aircraft

GROUND TRANSPORTATION

- Intelligent Transportation System – IVHS
- Improved emergency services
- Vehicle position/location for navigation tracking and monitoring
- Special travel information
- Vehicle control systems: position, location and velocity
- Highway facility and maintenance
- Accident location studies
- Highway construction
- Truck fleet on-the-road management
- "You Are Here" mapping displays
- In-vehicle wireless voice systems
- Monitoring status of bridges
- Guidance for robotic systems
- Stereosonic navigation for the blind

HEALTH CARE

- Tracking disease spread/distribution
- Epidemiological mapping
- Immediate position/location of medical personnel and specialists
- Personal navigation for blind persons
- Analytical medical modeling
- Precise timing in med-lab tests

LAW ENFORCEMENT AND SAFETY

- Dispatch of ambulance, police and fire department personnel and equipment
- Tracking/recovery of stolen vehicles
- Improved emergency response time
- Tracking movement of contraband
- Border surveillance
- Locating disabled vehicles for road services
- Security of high government officials and dignitaries while traveling
- Monitoring of severe weather
- Emergency evacuation planning
- Flood level and damage assessment
- Monitoring of game preserves and protected fishing grounds

MARITIME AND WATERWAYS

- Navigation on the high seas
- Search and rescue
- All weather harbor navigation approach
- Vessel traffic services
- Dredging of harbors and waterways
- Positioning of buoys and nav-aids
- Location of commercial fishing traps and nets
- Harbor facility management
- Enhanced Loran C marine navigation
- Offshore drilling research
- Monitoring deflections in dams caused by hydrostatic and thermal stresses
- Monitoring icebergs and rouge flows
- Precision ice breaking operations
- Observing tides and currents
- Precise navigation of inland waterways
- Locations of shipping containers

MINING AND EXCAVATION

- Electronic marking of geological events
- Accurate stockpile record keeping
- Precision location for mining explosives

PUBLIC TRANSPORTATION

- Bus fleet on-the-road management
- Railroad fleet monitoring
- Train control and collision avoidance

- Improved operator/passenger security
- Recording of truck travel across state lines for automatic tax billing

RECREATION AND SPORTS

- Hiking and mountain climbing
- Measuring at sporting events
- Setting lines on sports fields
- Relocating favorite fishing spots
- Wilderness search and rescue
- Electronic compassing for orientation
- Finding historic locales in wilderness

SCIENCE, TECHNOLOGY AND SPACE

- Measurement of sea level from satellites
- Navigating and control of space shuttles
- Placing satellites into orbit
- Monitoring earthquakes and tetonic plates
- Measuring ground subsidence
- Measuring river flood crests
- Measuring atmospheric humidity from the ground
- Precise global mapping of the ionosphere
- Users weather balloon position radiosonde
- Precise atomic laboratory timing
- Spacecraft attitude control

SURVEYING AND MAPPING

- Electronic bench marking for absolute latitude, longitude and altitude
- Single-handed high precision surveys
- Hydrographic surveying
- Efficient and accurate photo surveys
- Area measurement without triangulation
- Oil and mineral prospecting
- Measuring and recording of property boundaries
- National Spatial Data Infrastructure
- Real time DPS with regional point network reference stations
- Roadway profiling with kenematic GPS
- Integration with GIS for more reliable mapping and data collection

CHANGING TIMES

-- GPS is being integrated into almost every aspect of everyday life.

-- GPS sensors are becoming integrated with other technologies to provide solutions and new capabilities.

-- Existing regulatory and standards setting bodies may be inadequate in some instances to accommodate the broad reach of GPS applications.

-- A new policy perspective is required on a national and international level to coordinate and accommodate the commercial, consumer and strategic requirements in a global context.

MAKING IT UP AS WE GO ALONG

-- Technology and applications are still emerging

-- GPS is the first truly global utlity under single nation management

-- National decisions have global implications

-- Existing public, national and international policies have not kept pace

NEW QUESTIONS REQUIRE NEW ANSWERS

I DIDN'T KNOW THAT !!

-- Neither government nor industry know everything

-- Nobody tries to look stupid

MILITARY - Strategic & battlefield threats

CIVIL - Regulatory, public service

INDUSTRY - Technology, markets

NEED FOR DIALOGUE

MILITARY

SMART
DECISIONS

INDUSTRY

CIVIL

VOICE OF EXPERIENCE - DIALOGUE WORKS

Major US policy decisions have been based on dialogue

Export controls

Augmentation Study

DoD/DoT Task Force

NAPA/NRC Studies

RAND Study

PDD

FACTS OF LIFE

-- GPS improves war fighting capability

-- GPS is being adopted worldwide in industry and public infrastructure

-- GPS is being integrated with a wide variety of existing and emerging technologies

-- GPS industry is now creating real money $ $ $

The Question of L-5

NEED -- Military; Civilian

COST -- Direct: Satellite payload; hardware; etc.
Indirect: Changeover of installed base; infrastructure support

SECURITY -- Impact on military operations; safeguards against misuse

MARKET IMPACT -- Minimize disruption to user community; ensure compatibility of installed base

THE QUESTION OF L-5

-- US GPS industry is satisfied with the current signal structure and conditions of civilian use of the L-2 frequency.

-- USGIC fully supports exclusive military control of the L-2 frequency as critical to sustaining the military equity in GPS and the dual-use synergy that successfully benefits ALL equities.

-- USGIC would support a national security or public safety rationale for L-5 and would welcome working with US authorities to ensure a smooth transition to any new signal structure.

WE ARE NO LONGER ALONE

-- GPS technology, industry and applications have grown relatively unhindered by competing or existing technologies.

-- Success, however, has increased the breadth of bodies interested in managing GPS policy.

-- Real money ($ I Billion +) + Broad applications = Many more cooks.

-- In the near future GPS policy, regulation and standards will be influenced by <u>non-GPS</u> groups !

-- Prominent single application users (e.g. air transport) or competing/conflicting technologies (satcom), may dominate policy choices without accommodating other users.

-- National or regional security/commercial concerns may slow acceptance of GPS into overseas markets.

Early coordination is essential to maintain open markets and ensure global acceptance.

GPS and its Application to Railroad Operations, FRA, 1996 -06-
Signals, Control & Communications