What You Didn't Know about GPS and Its Augmentations

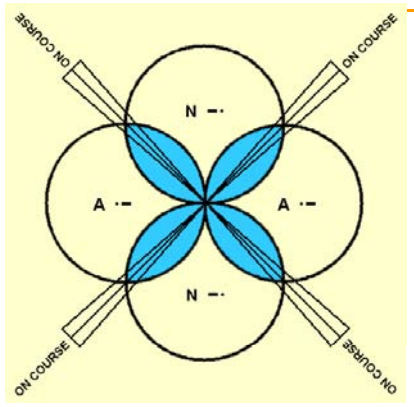
Vince Massimini *Rick Niles*

June 2009

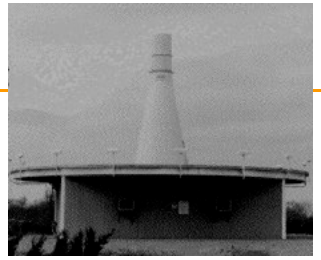
Overview

- GPS accuracy and integrity
- GPS and augmented GPS services
- GPS legalities
- GPS procedures (and plans for future procedures)
- Area Navigation (RNAV) and Required Navigation Performance (RNP)
- Future GPS and augmentations

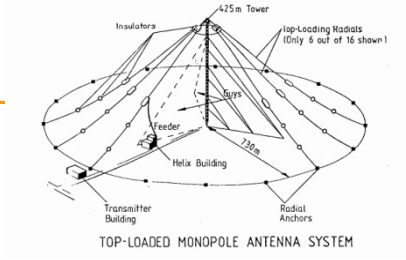
Overview - Navigation Aid Evolution



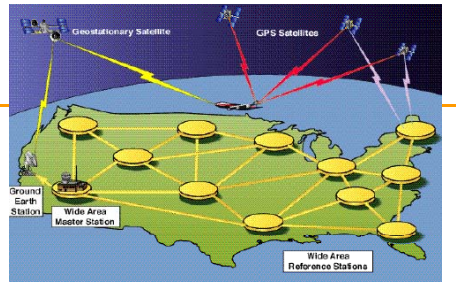
Four-course radio range



VORTAC

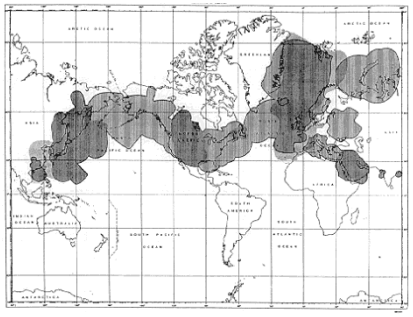


Omega



WAAS

NDB



LORAN-C

RAIM

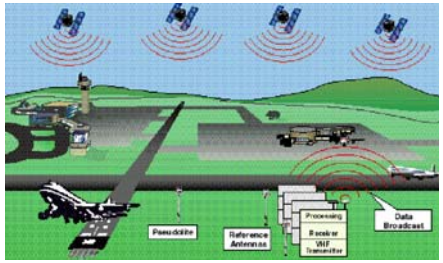
Galileo?

GRAS?

GPS

Beacon lights

Instrument Landing System



LAAS

1930 1940 1950 1960 1970 1980 1990 2000 2010 2020

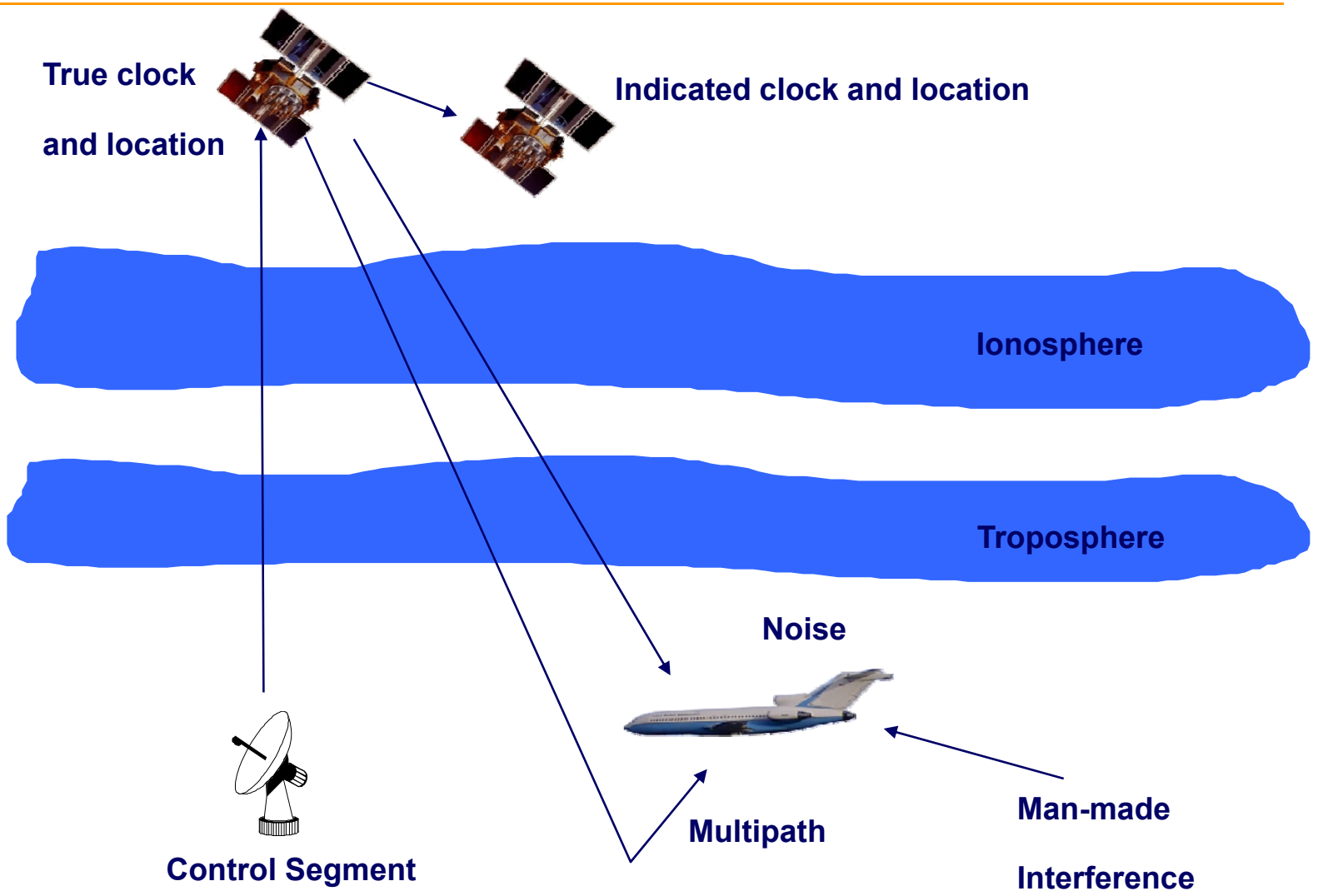
Global Navigation Satellite System (GNSS)

- **Global Positioning System (GPS) (U.S.)**
  - Nominally 24 satellites in 6 orbital planes inclined 55 degrees
  - Operational for civil aviation since 1994
- **GLONASS (Russian)**
  - Nominally 21 satellites in 3 orbital planes inclined 45 degrees
    - Uneven sustainment for many years; fully operational in 2009(?)
- **Galileo (European Union)**
  - Nominally 27 satellites in 3 orbital planes inclined 56 degrees
  - Two test satellites in orbit; Operational in 2013 (?)
- **Compass (China)**
  - 5 current satellites; proposed mix of GEO and MEO satellites

GPS Constellation

- **Nominal constellation is 24 satellites in 6 planes**
  - **4 "slots" per orbit**
  - **Transmit ranging code on single frequency (L1:1575.42 MHz)**
- **32 satellites are flying right now (31 operational)**
- **The U.S. DoD commitment is:**
  - **> 24 satellites operational 95% of the time**
    - **Does not mean all 24 have a useable navigation signal**
  - **$\geq$ 21 slots filled with at least one satellite transmitting a useable navigation signal 98% of the time**
    - **$\geq$ 20 slots 99.999% of the time**
- **More later on the GAO report**

GPS Error Sources



The 1992 Political Slogan: It's the Economy, Stupid!!

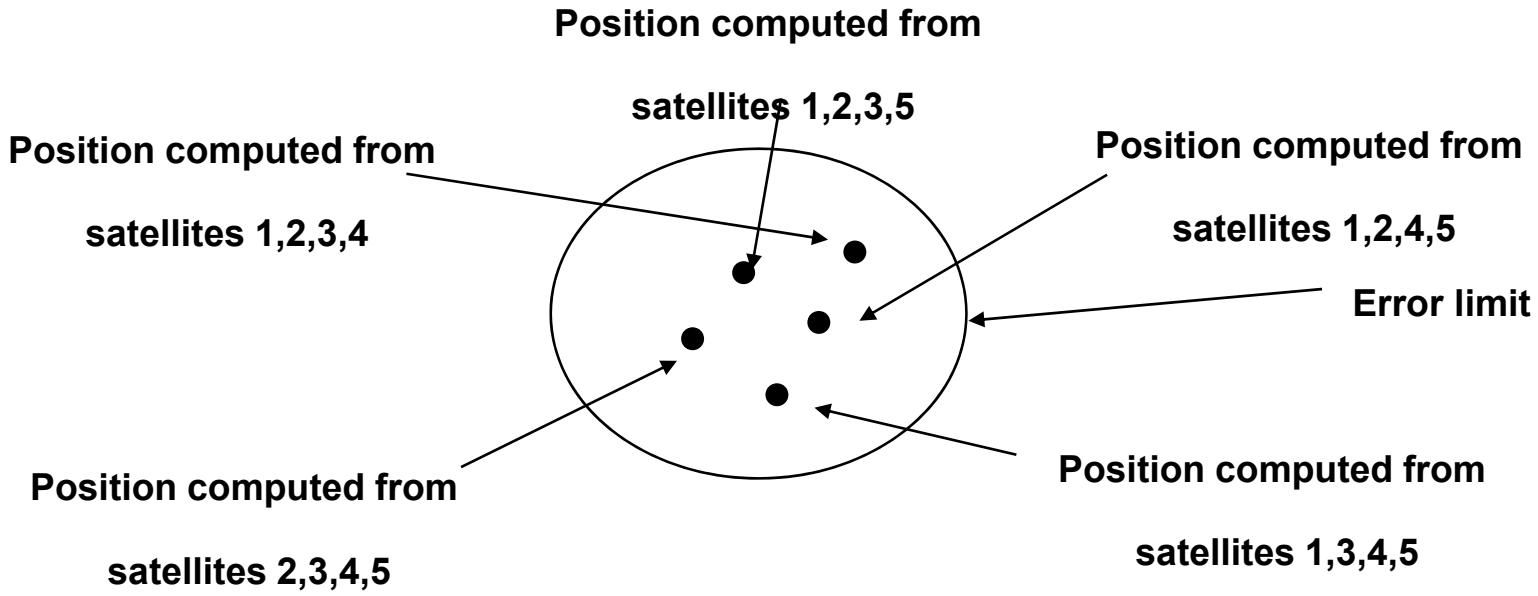
But Clinton Never Heard of Integrity

- **Accuracy**
  - **GPS: ~2-3 m horizontal and 4-6 m vertical**
- **GPS can have major errors (faults)**
  - **For example, a runaway clock on a GPS satellite could cause thousands of meters of error with no warning**
    - **Up to 6 hours for USAF to disable navigation signal**
    - **July 2001—clock problem caused errors of 2,000 – 3,000 km**
- **Integrity: Ability of a system to provide service within known limits or to notify the user that the system is out of tolerance.**

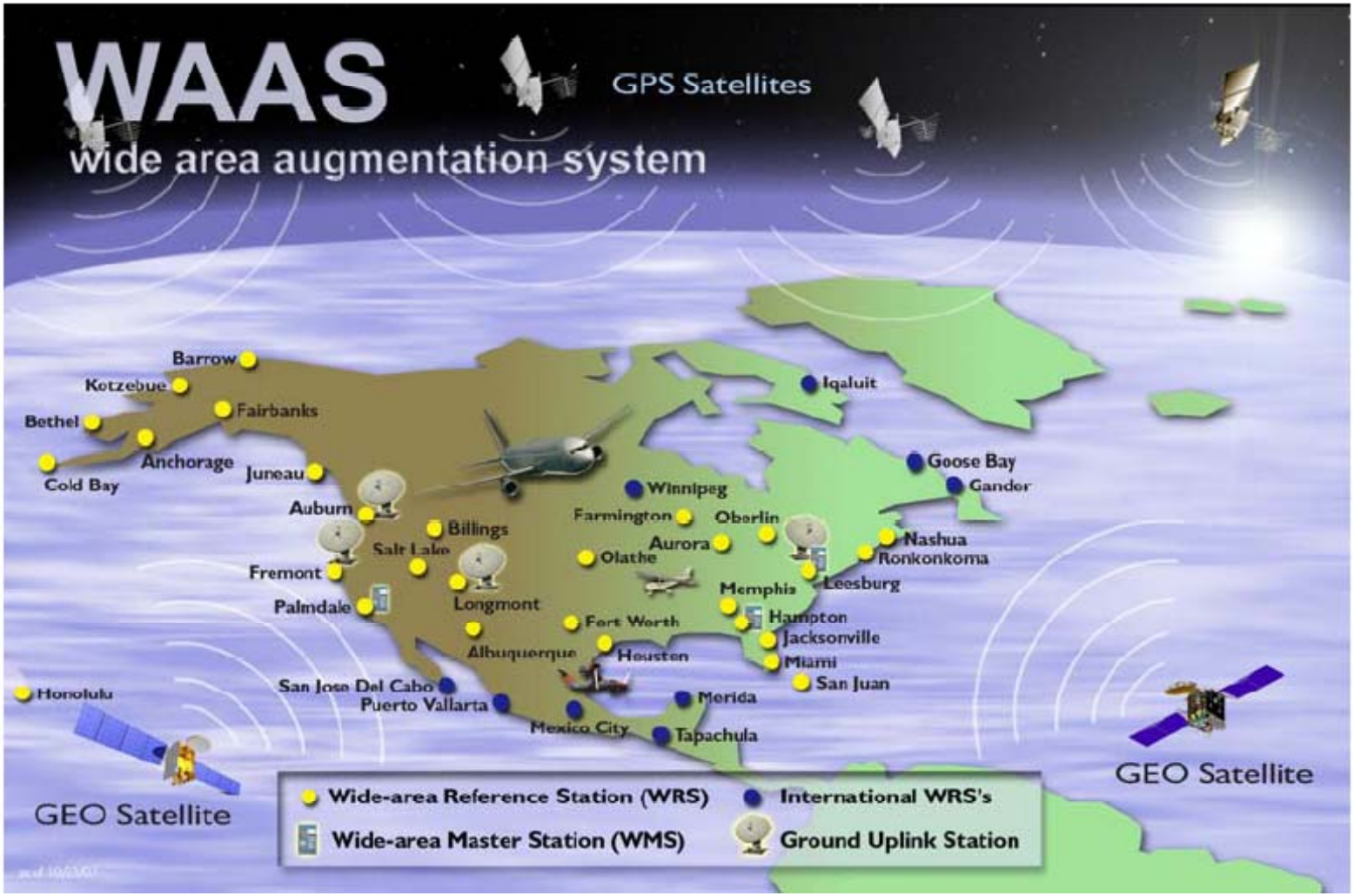
Augmentation Systems

Receiver Autonomous Integrity Monitoring (RAIM)

- **Four satellites can provide position and time**
- **With 5 satellites, users can calculate positions using groups of four and *compare* the positions**
  - **Barometric aiding can reduce this to four satellites**
- **With ≥ six satellites, users can identify and eliminate a bad satellite**

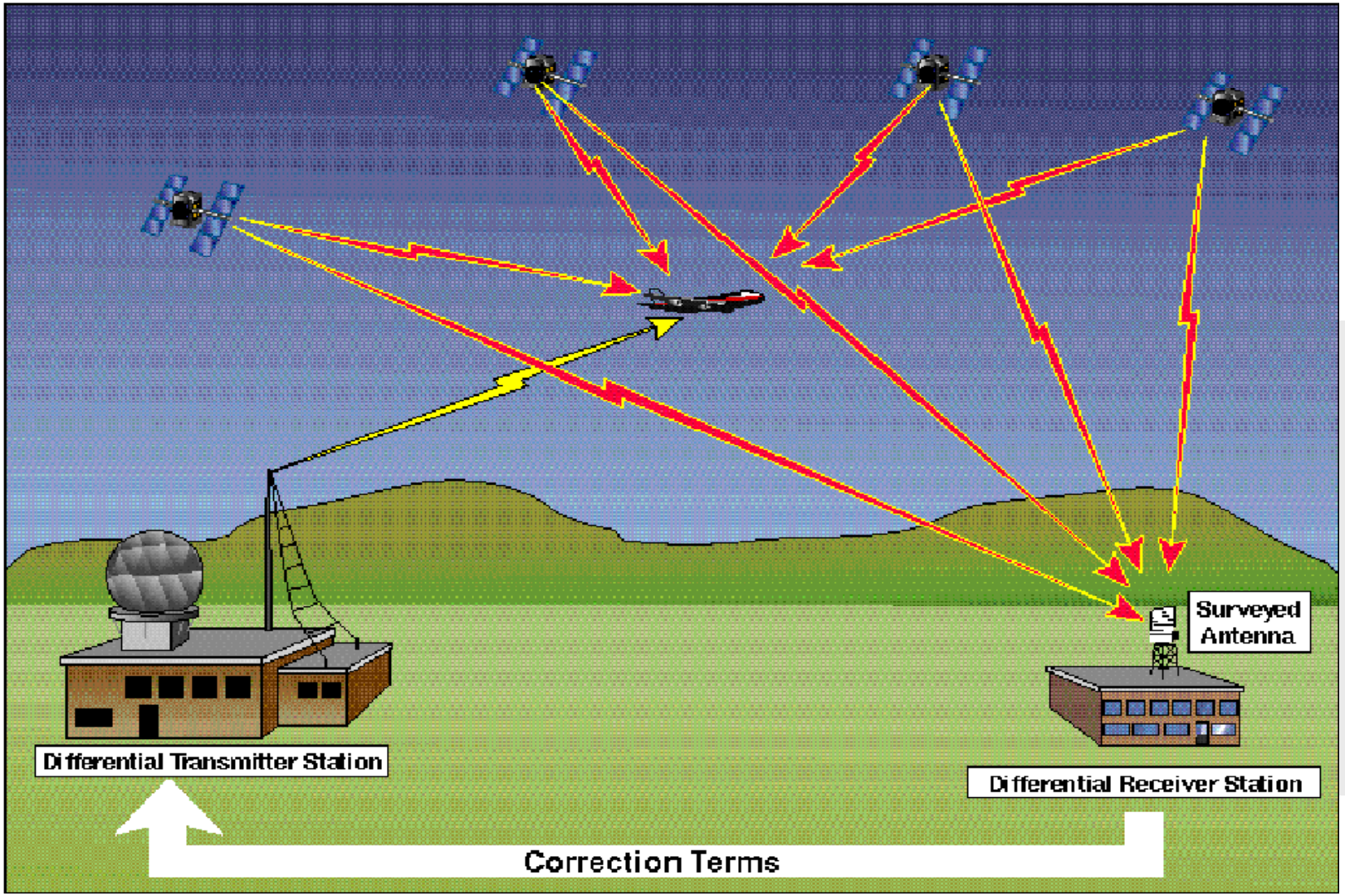


Wide Area Augmentation System (WAAS)



Source: Federal Aviation Administration

Local Area Augmentation System (LAAS)



What do WAAS and LAAS Do?

- Ground stations listen for errors on GPS satellites
- WAAS
  - Errors from ground stations are transmitted to master stations (3 total master stations) which
    - Compute orbit and clock errors of each satellite
    - Create a grid of ionospheric errors over the U.S.
  - A GEO satellite receives and retransmits to users via L1:
    - Orbit and clock errors for each satellite
    - Grid of ionospheric errors
    - Integrity warnings of bad satellites
  - The GEO satellite also transmits a GPS-like ranging signal
- LAAS
  - A total error for each satellite is transmitted to users near the LAAS station via a VHF data link signal

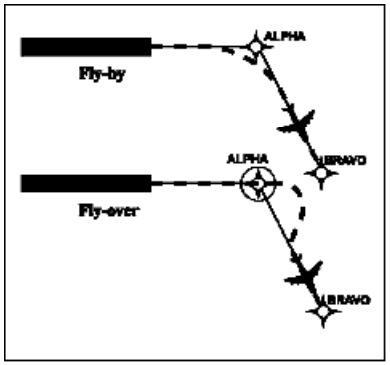
What are the Effects of WAAS and LAAS?

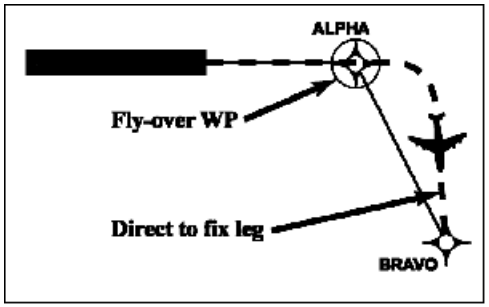
- **Extra ranging from Geo satellites**
  - **Equivalent to 2 – 4 extra GPS satellites in USA**
- **Integrity warning is from WAAS or LAAS**
  - **RAIM is not required (i.e., fewer satellites are required)**
- **Improved accuracy and integrity**
  - **Accuracy**
    - **GPS: ~2-3 m horizontal and 4-6 m vertical**
    - **WAAS: ~.5 m horizontal and 1 m vertical**
  - **Integrity (maximum allowable un-alarmed error)**
    - **GPS LNAV Approach: 556 m integrity limit (horizontal only)**
    - **WAAS LPV Approach: 40 m horizontal and 50 or 35 m vertical**
    - **LAAS GLS Approach: 40 m horizontal and 10 m vertical**

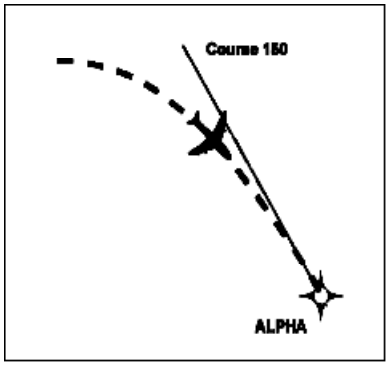
RNAV Benefits/Services

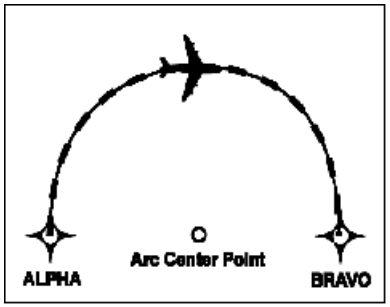
RNAV Leg Types

- Track to Fix (TF)
- Direct to Fix (DF)
- Course to Fix (CF)
- Radius to Fix (RF)
- Heading (VA)

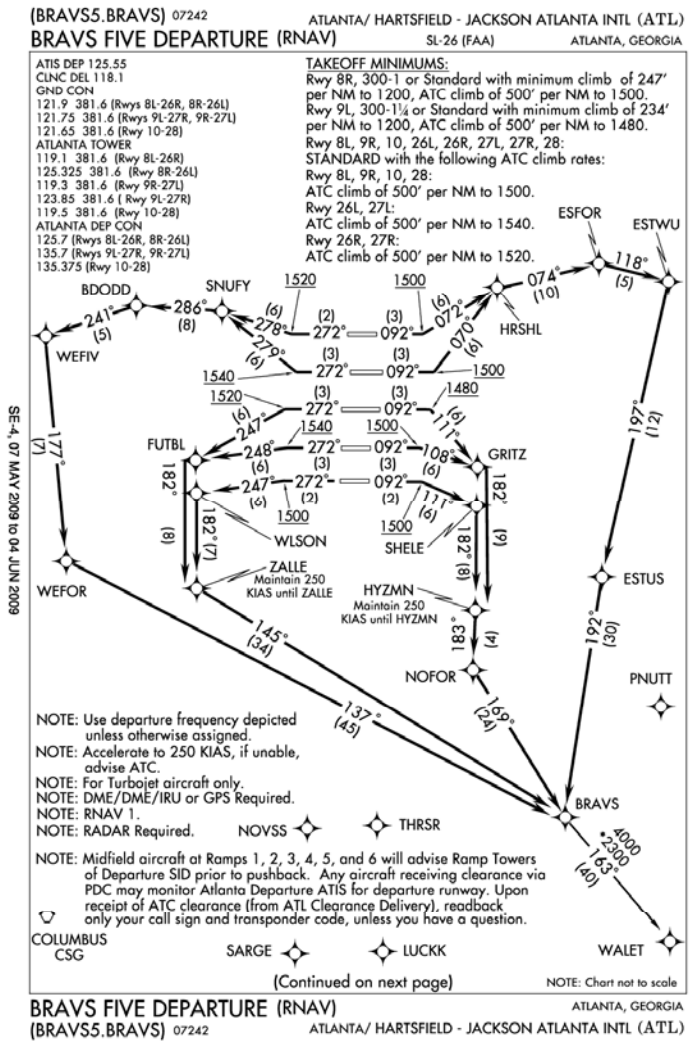


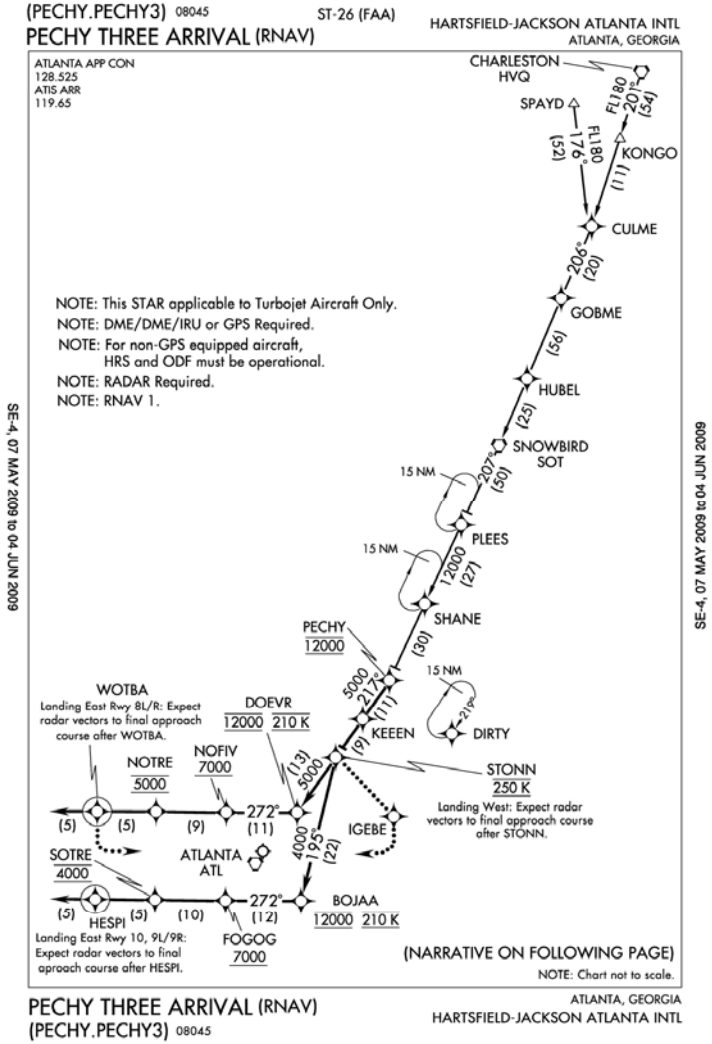




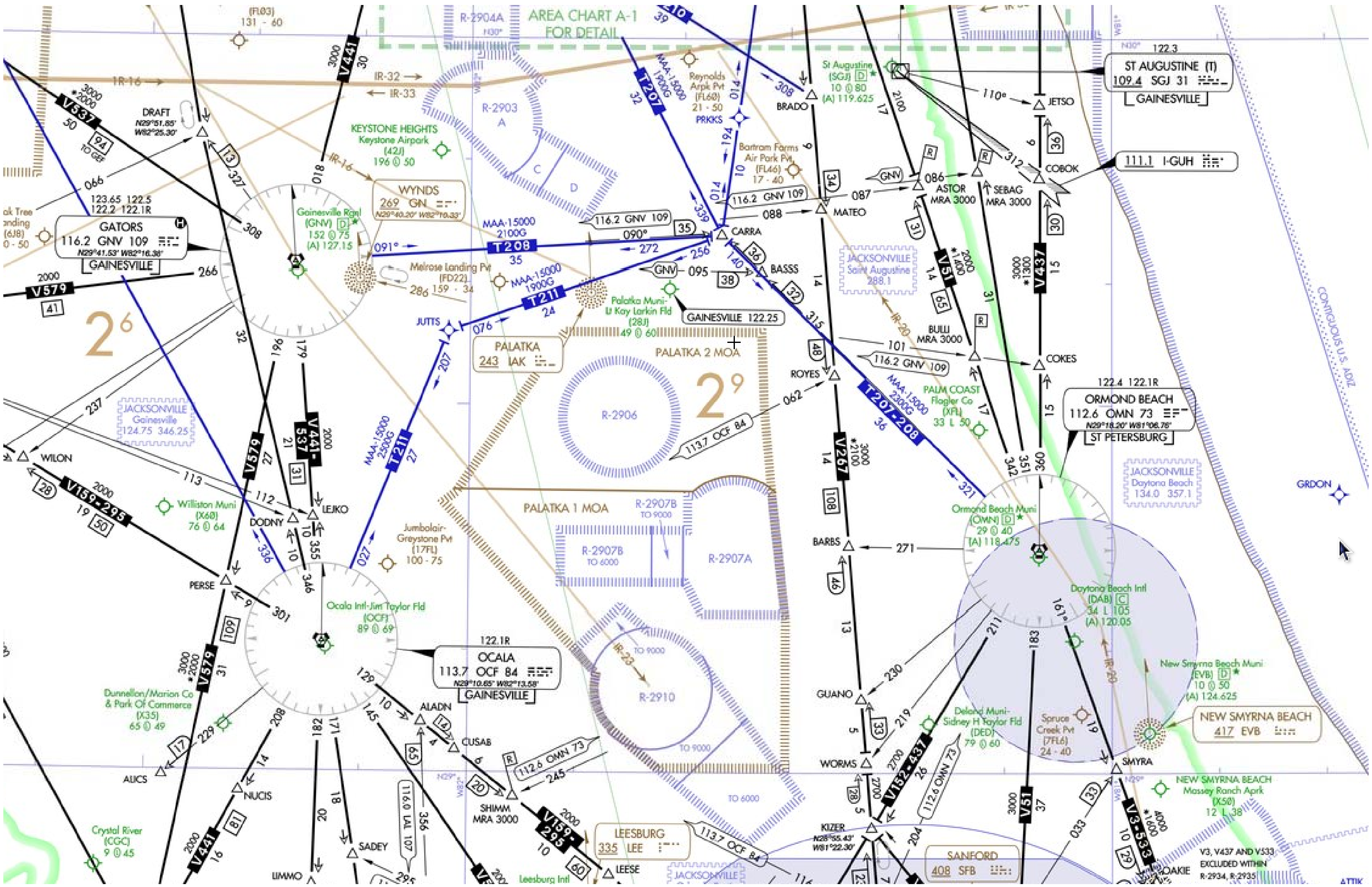


RNAV DPs and STARS





T Routes


AREA CHART A-1
FOR DETAIL
R-2904A
R-2903
ST AUGUSTINE (T)
109.4 SGJ 31
GAINESVILLE
111.1 I-GUH
GATORS
116.2 GNV 109
N29°41.53' W82°16.38'
GAINESVILLE
WYNDS
269 GN
KEYSTONE HEIGHTS
Keystone Airpark
(42J)
196 L 50
Gainesville Rgnl
(GNV)
152 L 75
(A) 127.15
MAA-15000
2100G
T208
35
MAA-15000
1900G
T211
24
T207
MAA-15000
1900G
32
T207-208
MAA-15000
2300G
36
116.2 GNV 109
090°
272
CARRA
088
MATEO
087
ASTOR
MRA 3000
SEBAG
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COBOK
JETSO
BRADO
BASSS
ROYES
COKES
BULLI
MRA 3000
PALM COAST
Flagler Co
(XFL)
33 L 50
JACKSONVILLE
Saint Augustine
288.1
GAINESVILLE 122.25
Palatka Muni-
Lt Kay Larkin Fld
(28J)
49 L 60
PALATKA
243 IAK
PALATKA 2 MOA
PALATKA 1 MOA
R-2906
R-2907B
TO 9000
R-2907B
TO 6000
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R-2910
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JUTTS
DRAFT
N29°51.85'
W82°25.30'
WILON
DODNY
LEJKO
PERSE
JACKSONVILLE
Gainesville
124.75 346.25
Williston Muni
(X60)
76 L 64
Jumbolair-
Greystone Pvt
(17FL)
100 - 75
Melrose Landing Pvt
(FD22)
159 - 34
Ocala Intl-Jim Taylor Fld
(OCF)
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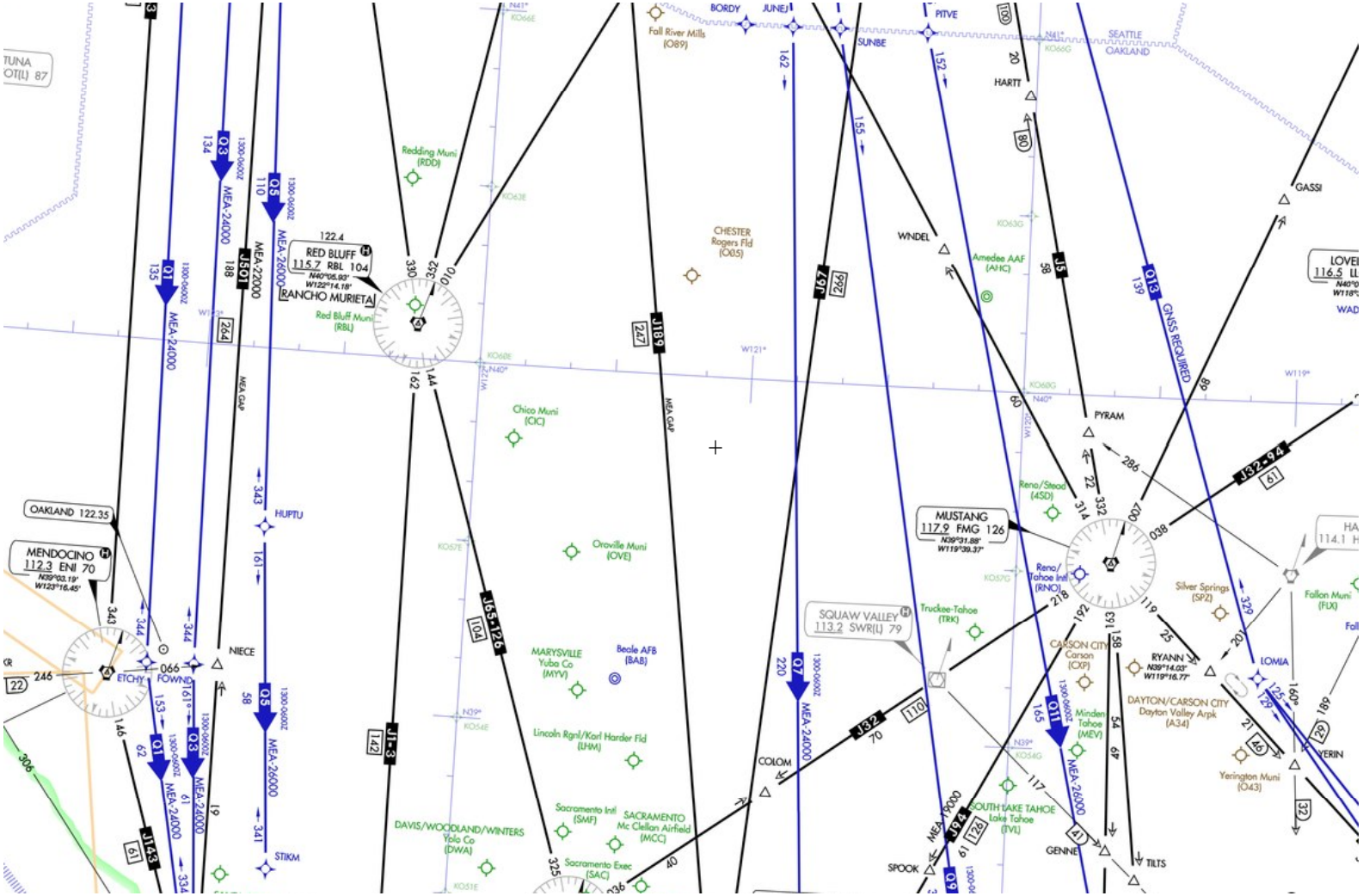
OCALA
113.7 OCF 84
N29°10.65' W82°13.58'
GAINESVILLE
122.1R
Dunnellon/Marion Co
& Park Of Commerce
(X35)
65 L 49
Crystal River
(CGC)
9 L 45
ALICS
NUCIS
ALADN
CUSAB
SHIMM
MRA 3000
SADEY
LIMMO
LEESE
LEESBURG
335 LEE
Leesburg Intl
ORMOND BEACH
112.6 OMN 73
N29°18.20' W81°06.76'
ST PETERSBURG
122.4 122.1R
Ormond Beach Muni
(OMN)
29 L 40
(A) 118.475
JACKSONVILLE
Daytona Beach
134.0 357.1
Daytona Beach Intl
(DAB)
34 L 105
(A) 120.05
BARBS
GUANO
WORMS
KIZER
N28°55.43'
W81°22.30'
SMYRA
OAKIE
New Smyrna Beach Muni
(EVB)
10 L 50
(A) 124.625
NEW SMYRNA BEACH
417 EVB
NEW SMYRNA BEACH
Massey Ranch Arpk
(X50)
12 L 38
Deland Muni-
Sidney H Taylor Fld
(DED)
79 L 60
Spruce
Creek Pvt
(7FL6)
24 - 40
SANFORD
408 SFB
112.6 OMN 73
V3, V437 AND V533
EXCLUDED WITHIN
R-2934, R-2935
GRDON
CONTIGUOUS U.S. ADIZ
V537
V579
V441
V441-537
V159-295
V267
V51
V437
V152-437
V3-533

Q Routes


BORDY
JUNEJ
PITVE
SUNBE
SEATTLE
OAKLAND
HARTT
GASSI
WINDEL
Amedee AAF (AHC)
CHESTER Rogers Fld (O05)
Redding Muni (RDD)
Fall River Mills (O89)
RED BLUFF
115.7 RBL 104
RANCHO MURIETA
Red Bluff Muni (RBL)
Chico Muni (CIC)
Oroville Muni (OVE)
MARYSVILLE Yuba Co (MYV)
Beale AFB (BAB)
Lincoln Rgnl/Karl Harder Fld (LHM)
DAVIS/WOODLAND/WINTERS Yolo Co (DWA)
Sacramento Intl (SMF)
SACRAMENTO Mc Clellan Airfield (MCC)
Sacramento Exec (SAC)
OAKLAND 122.35
MENDOCINO
112.3 ENI 70
ETCHY
FOWNE
NIECE
HUPTU
STIKM
COLOM
SQUAW VALLEY
113.2 SWR(L) 79
Truckee-Tahoe (TRK)
SOUTH LAKE TAHOE Lake Tahoe (TVL)
SPOOK
GENNE
TILTS
MUSTANG
117.9 FMG 126
Reno/Stead (4SD)
Reno/Tahoe Intl (RNO)
CARSON CITY Carson (CXP)
Minden Tahoe (MEV)
RYANN
DAYTON/CARSON CITY Dayton Valley Arpk (A34)
Silver Springs (SPZ)
Fallon Muni (FLX)
LOMIA
Yerington Muni (O43)
GNSS REQUIRED
MEA GAP
MEA-24000
MEA-26000
MEA-22000

File and Fly Direct

- Radar coverage required in CONUS
- Currently FAA automation requires at least one fix in each ARTCC
- Example routes
  - KFME WOOLY V214 MRB CTW I40
  - KFME GRACO V93 PXT V213 TAPPA KCPC
- ATC may clear you direct beyond center boundary to destination
  - Will need “heading to destination”
    - They actually mean ground track bearing

RNAV Approaches

- **No ground based navigation aids required**

- **LNAV**
  - **WAAS (TSO-145/146) or GPS (TSO-C129) receiver required**
  - **Near 100% availability with WAAS (not with only GPS (TSO-C129)**

- **LNAV/VNAV**
  - **Either WAAS (TSO-145/146) receiver or GPS (TSO-C129) receiver with approved barometric vertical navigation (Baro VNAV) system required**

RNAV Approaches

- **LPV**
  - **WAAS (TSO-145/146) receiver required**
  - **Minimums as low as 200 ft above the touchdown zone**
    - **Should never be higher than an ILS**
- **LP**
  - **WAAS (TSO-145/146) receiver required**
  - **Allows for non-precision approach with low minimums**
  - **Used when an obstacle prevents LPV and minimum is at least 20 feet lower than the equivalent LNAV approach**
- **Required Navigation Performance (RNP)**

What is RNP?

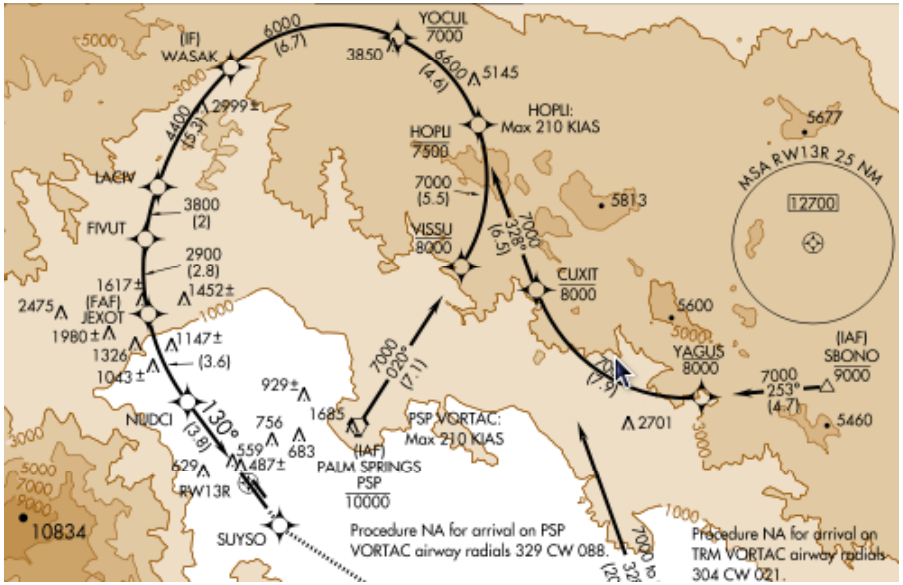
- **RNP is RNAV with on-board navigation monitoring and alerting**

- **RNP has a specific "performance level"**
  - **e.g. RNP 2 means the aircraft will be within 2.0 NM of the centerline of the route 95% of the time**
  - **This includes the combination of both navigation system performance and flight technical error (pilot error)**

- **GPS and WAAS receivers are approved for RNP 0.3 and above**
  - **RNP with Authorization Required (AR) currently approved to RNP 0.1**

RNP Approaches

- **Standard RNP approach**
  - **None ever published**
- **137 RNP (SAAAR) approaches published (7 May 2009)**
  - **Valuable for mountainous terrain with curved segments**



GPS Legalities

Handheld and VFR Panel Mount GPSs

VFR Flight

- **GPS use for VFR flight is generally unregulated by the FAA**
  - **Strictly advisory**
  - **PIC must ensure that PDAs do not interfere with aircraft systems**
- **Few, if any, handheld GPSs have integrity monitoring**
  - **Look out of the window!!**
- **Panel mount VFR GPSs have no operational differences from handhelds**
  - **Installed antenna may give better reception**

Handheld and VFR Panel Mount GPSs

IFR Flight

- **Advisory use only**
  - **Aircraft must carry appropriate avionics for ground navigation aids to be used in the flight**
  - **No /G equipment code**
  - **Cannot file to RNAV-only waypoints or fly RNAV approaches**

- **Radar vectors can be used**
  - **"Center, request radar vectors to LAX VOR; heading is 277º"**
  - **"N12345 fly heading 277 direct LAX, report receiving"**

  - **"N12345 fly direct WALLO flight plan route"**
  - **"Potomac, N12345 is not RNAV; request vectors to WALLO; heading is 330º"**
  - **"N12345 fly heading 330 direct WALLO**

IFR GPS Requirements

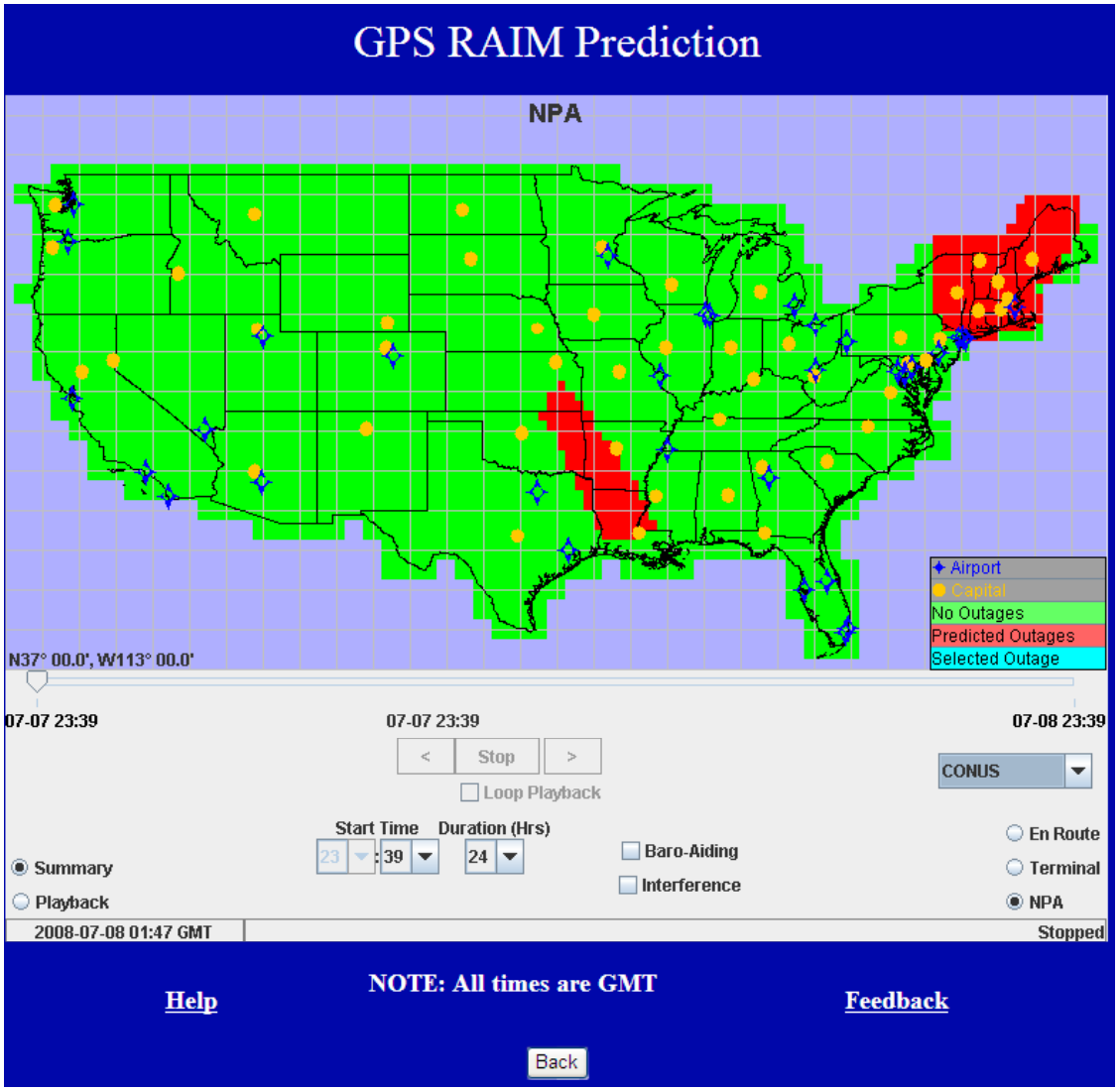
- **GPS (TSO-C129 (non-WAAS))**
  - Installed IAW AC 120-38
  - Must maintain avionics necessary to receive ground based navigation aids (including 30-day VOR check)
- **WAAS (TSO 146)**
  - Installed IAW AC 120-38a
  - Approved as sole means of navigation
    - No requirement to carry VOR, ILS, ADF, etc. or other avionics necessary to receive ground navigational aids
    - Check AFM—some 430Ws have a temporary restriction
- **A current database is required for IFR use**
  - Unless the FAA-approved AFM indicates that waypoints can be checked manually

IFR GPS Requirements

1 of 2

- **A number of requirements have been changed in the last few years that facilitate GPS use**
  - **14CFR 91.131: a VOR is no longer required in Class B airspace--an approved RNAV system is now acceptable**
  - **GPS can substitute for VOR (airways and waypoints)**
- **GPS has been an approved substitute for DME and ADF for several years**
  - **A VOR or NDB approach cannot legally be flown with a GPS--needs to be VOR or GPS/NDB or GPS**
  - **GPS cannot substitute for ILS or localizer**

www.raimprediction.net



IFR GPS Requirements

2 of 2

- **WAAS LPV approaches (*still!!*) cannot be used to satisfy the precision approach requirements in the PTS**
  - **Rick and I are both working to change this**

Preflight

Equipment Codes

- File /G if your aircraft has an IFR qualified GPS panel mounted receiver with current database
  - No equipment code is filed on a VFR flight plan
- Do NOT file /G
  - If your aircraft has only a VFR qualified GPS receiver
    - E.g., N781FM (GX 55)
  - If the database has expired (unless OK by AFM)
  - If you only have a hand-held GPS receiver
- You may file “/R”, but it will not do you any good since there are currently no RNP procedures that are not SAAAR.

Preflight Requirements

1 of 2

- **Navigation database must be up-to-date**
  - **Check on preflight**
- **GPS (TSO-C129) users must check GPS NOTAMS**
  - **Satellite outage or radio frequency interference**
  - **Must ask FSS or look online (for KNMH or KGPS)**
- **WAAS (TSO145/146) user must check WAAS NOTAMS**
  - **WAAS out of service, WAAS unreliable**
- **Before a TSO-C129 user flies an RNAV route they must check www.raimprediction.net**
  - **AC 90-100a**
  - **Or use manufacturer approved software**
- **Must file ICAO flight plan if flying an RNAV STAR or DP for both WAAS and GPS**

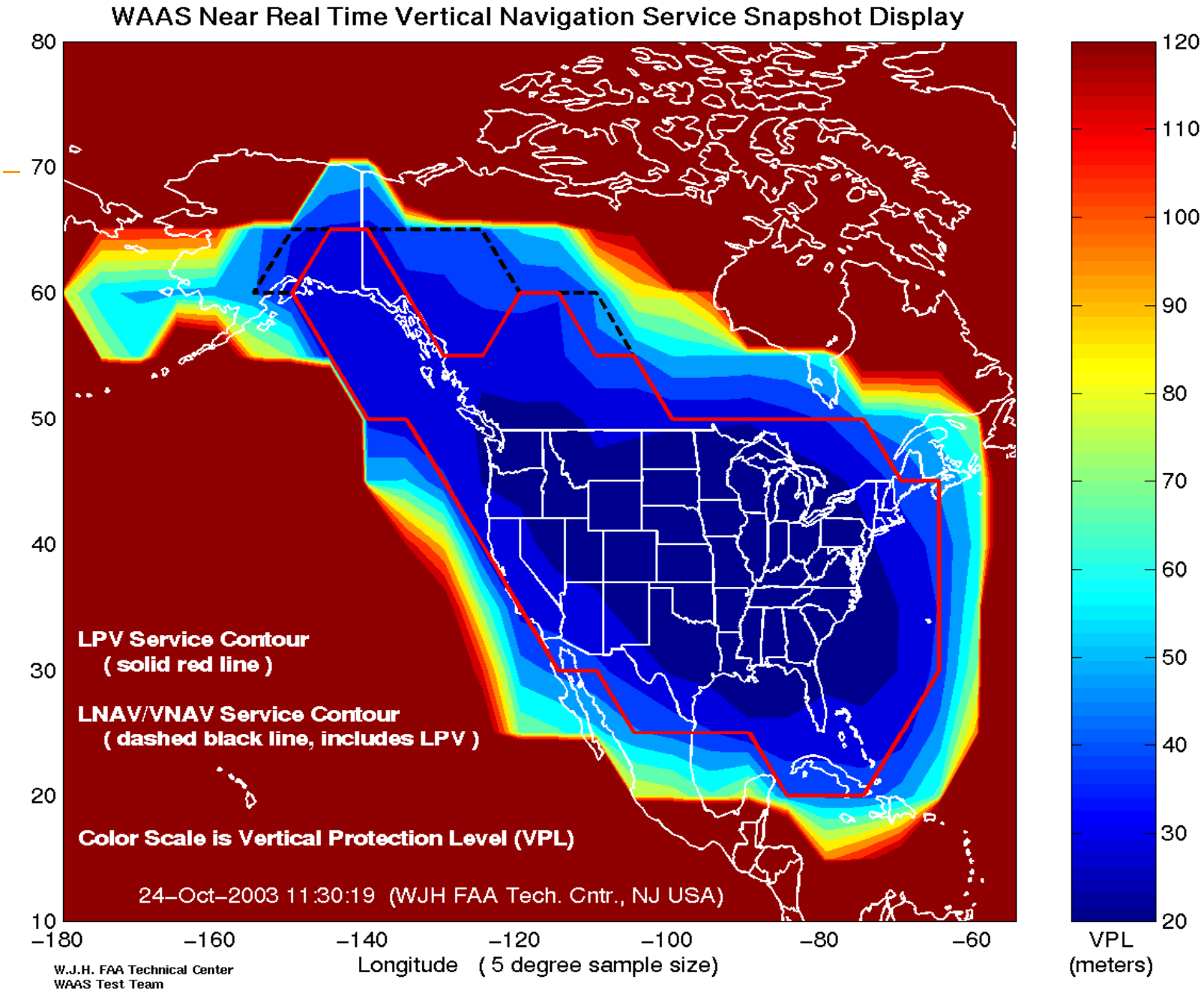
Preflight Requirements
2 of 2

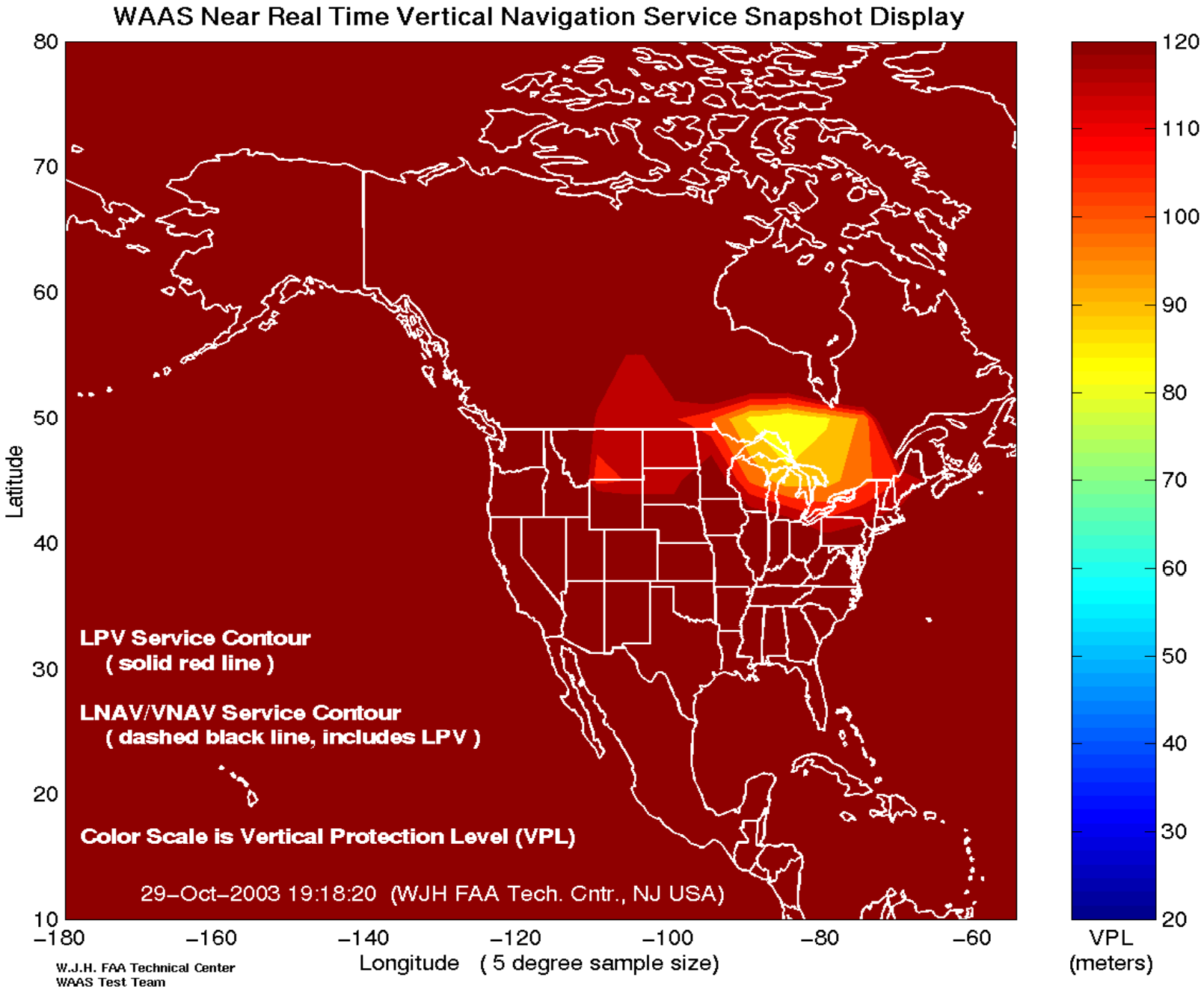
- **For GPS (TSO-C129): If an alternate airport is required, an approach must be available that can be flown without the use of GPS**
  - **Cannot use VOR, DME, or ADF unless approved and operational avionics are installed**
  - **Does not apply to WAAS (TSO-145) receivers**
    - **WAAS receivers may plan for LNAV at alternate**
      - **Except that some of the Garmin 400x series have a temporary flight manual restriction**

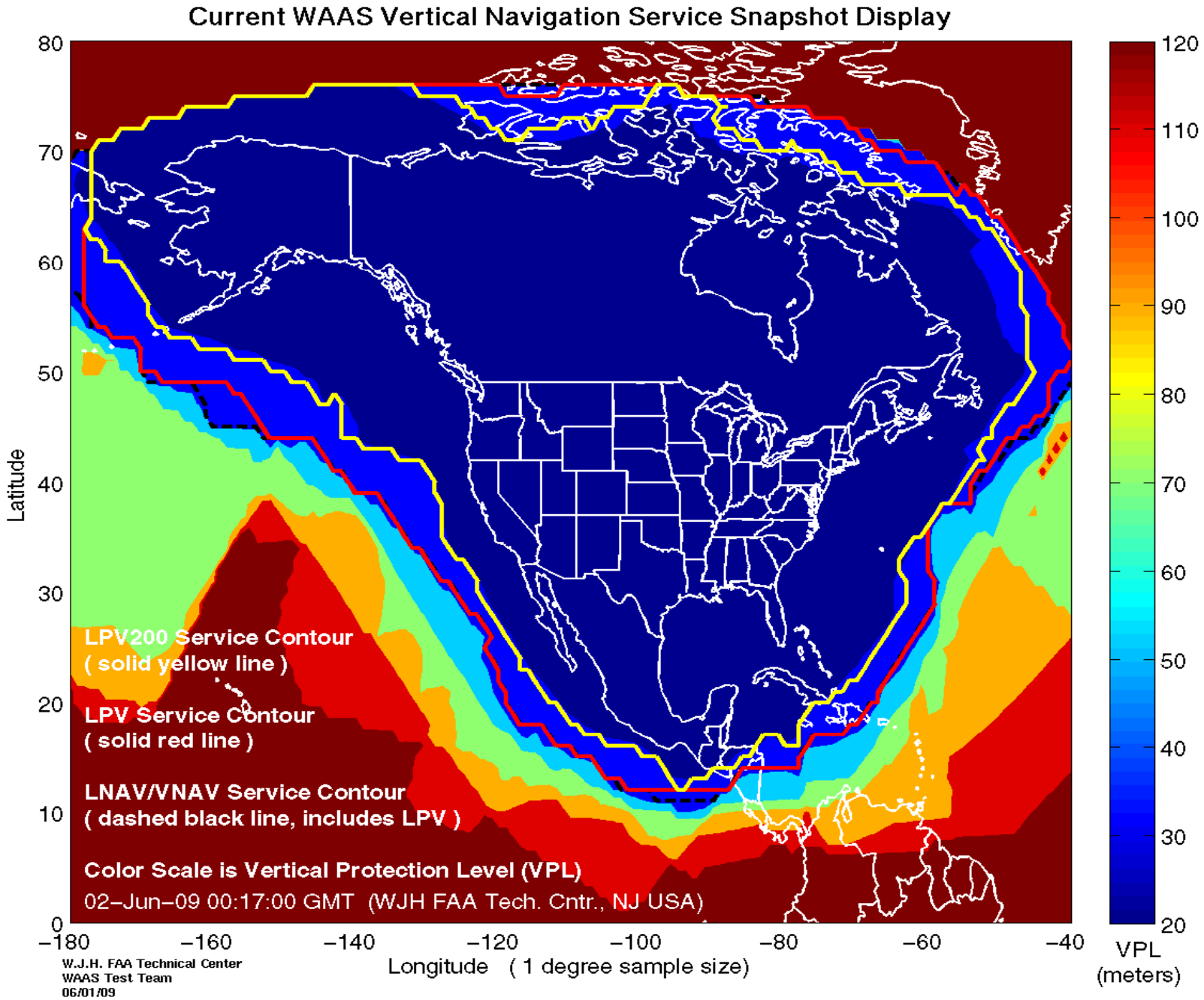
Future GNSS

Dual Frequency GPS

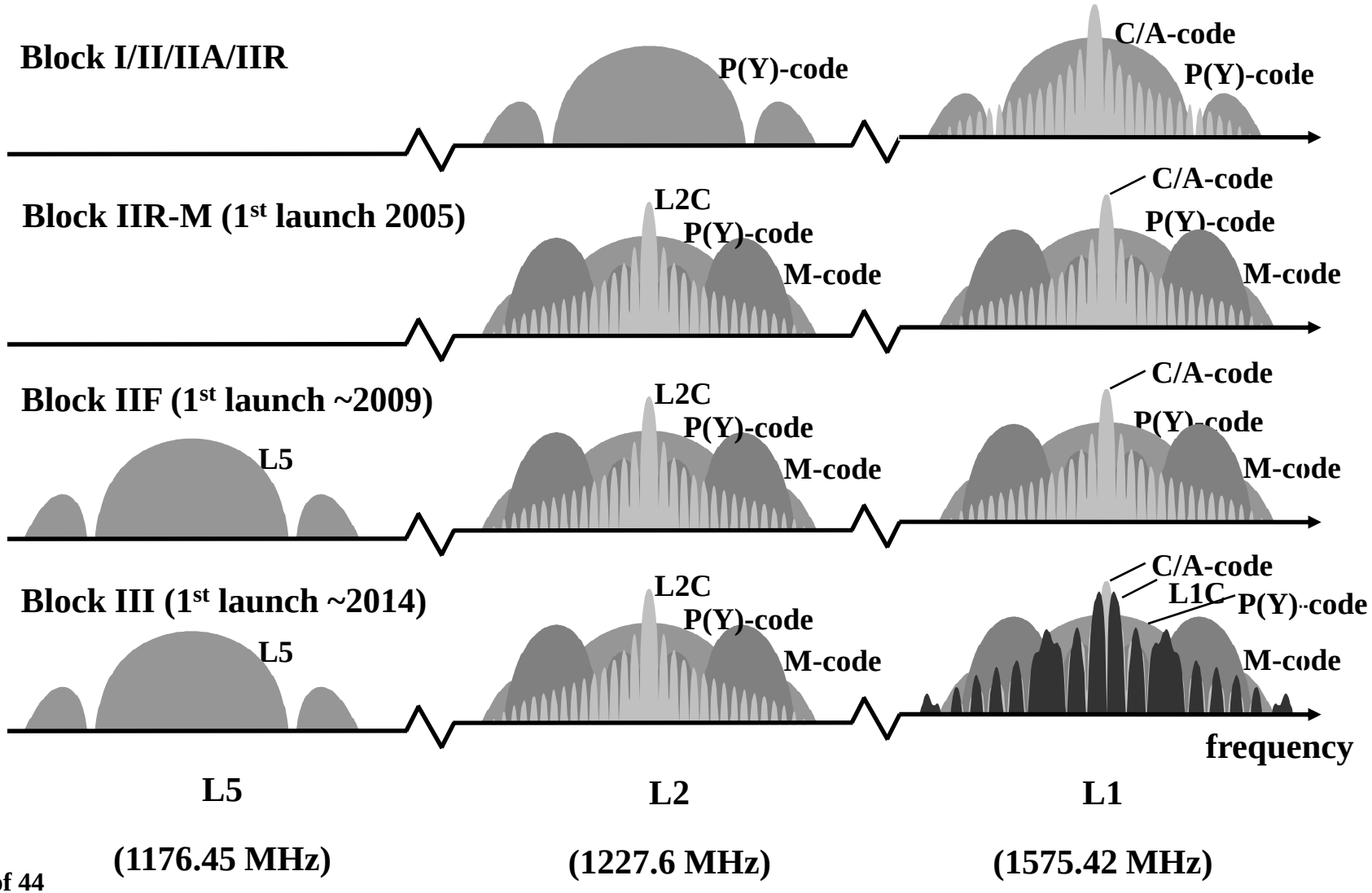
- Current receivers use the L1 frequency (1575.42 MHz)
  - Measures the range from each satellite
  - Range measurement affected by atmosphere
    - WAAS error grid allows user to interpolate to correct for these errors
- Two signals on two frequencies allow the user to correct for atmospheric range errors
  - No interpolation
  - System can be much more robust to atmospheric disturbances
- Second frequency also gives protection against inadvertent radio frequency interference


WAAS Near Real Time Vertical Navigation Service Snapshot Display
80
70
60
50
40
30
20
10
−180
−160
−140
−120
−100
−80
−60
Longitude (5 degree sample size)
LPV Service Contour
(solid red line)
LNAV/VNAV Service Contour
(dashed black line, includes LPV)
Color Scale is Vertical Protection Level (VPL)
24−Oct−2003 11:30:19 (WJH FAA Tech. Cntr., NJ USA)
120
110
100
90
80
70
60
50
40
30
20
VPL
(meters)
W.J.H. FAA Technical Center
WAAS Test Team
10/24/03


WAAS Near Real Time Vertical Navigation Service Snapshot Display
Latitude
80
70
60
50
40
30
20
10
−180
−160
−140
−120
−100
−80
−60
Longitude (5 degree sample size)
LPV Service Contour
(solid red line)
LNAV/VNAV Service Contour
(dashed black line, includes LPV)
Color Scale is Vertical Protection Level (VPL)
29−Oct−2003 19:18:20 (WJH FAA Tech. Cntr., NJ USA)
120
110
100
90
80
70
60
50
40
30
20
VPL
(meters)
W.J.H. FAA Technical Center
WAAS Test Team
10/29/03


Current WAAS Vertical Navigation Service Snapshot Display
Latitude
Longitude (1 degree sample size)
VPL
(meters)
LPV200 Service Contour
(solid yellow line)
LPV Service Contour
(solid red line)
LNAV/VNAV Service Contour
(dashed black line, includes LPV)
Color Scale is Vertical Protection Level (VPL)
02–Jun–09 00:17:00 GMT (WJH FAA Tech. Cntr., NJ USA)
W.J.H. FAA Technical Center
WAAS Test Team
06/01/09

GPS Signal Modernization



GPS Satellites

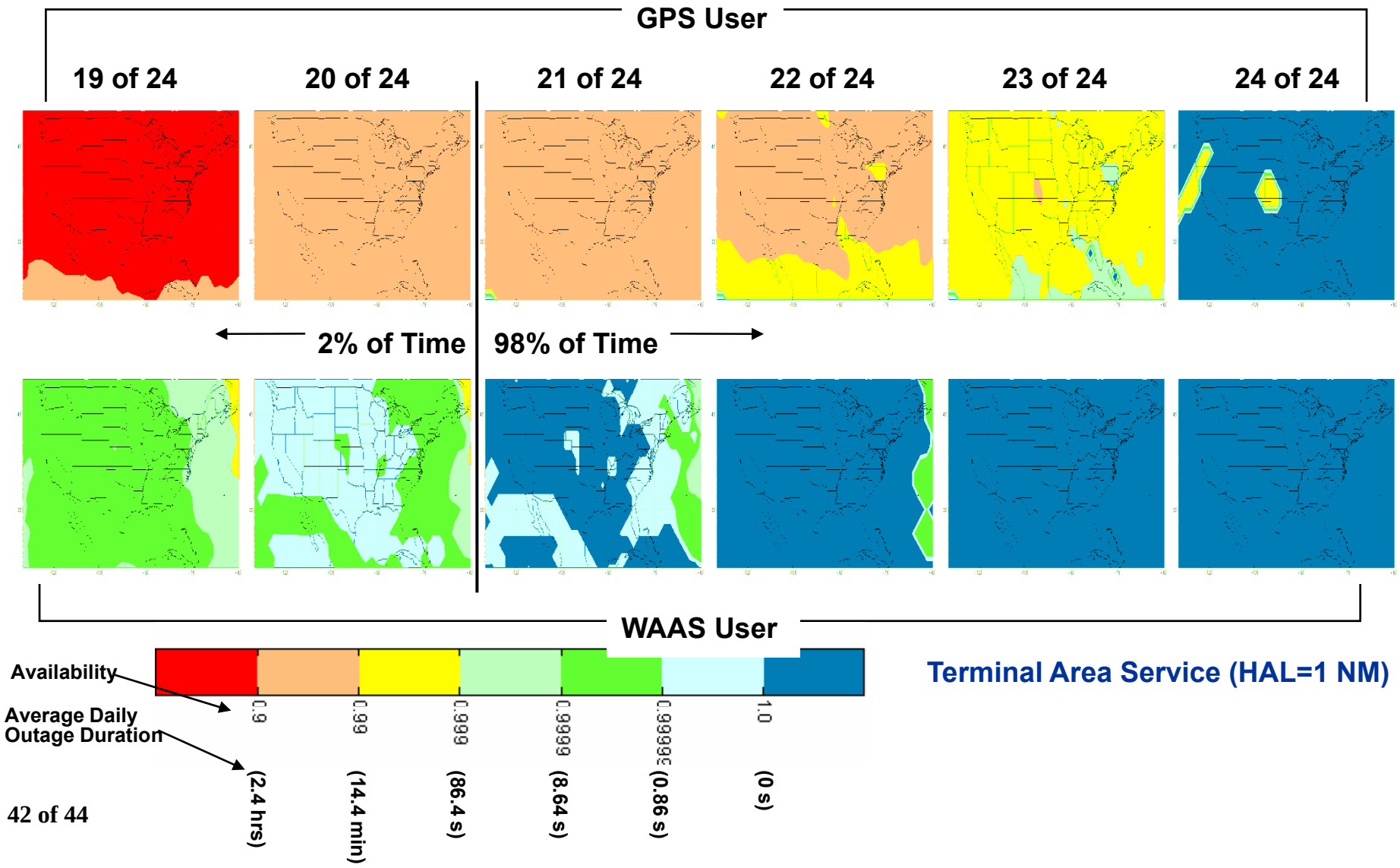
- 31 Operating satellites (IIA, IIR, IIR-Ms)
  - Many are "single string"
  - 32nd satellite (IIR-M) has some anomalies and is not yet operational after its March launch
- 1 more IIR-M ready for launch in August
- 12 IIF satellites are under contract by Boeing with first launch scheduled in January 2009
  - At least 3 years late with multiple problems and delays
- Contract for 12 GPS IIIa satellites just awarded to Lockheed Martin
  - First launch 2014 (faster planned development than IIFs)

GAO Report

- IIF contract had many problems
  - Other U.S. space contracts have problems also
- IIIa contract was awarded late and is compressed
  - 2014 launch may be optimistic
- Many flying satellites are old and 'single string'
- GAO Report:

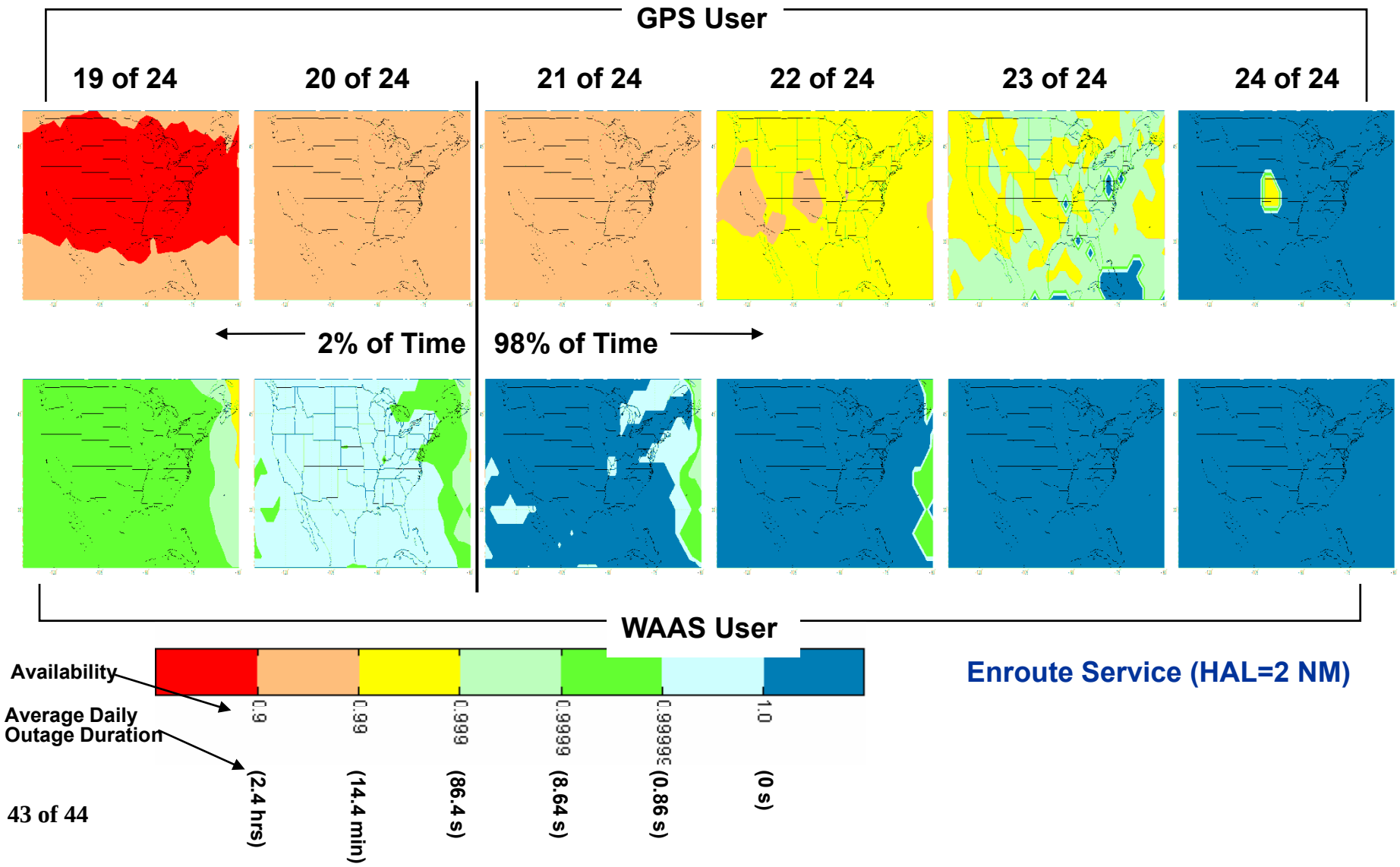
"Based on the most recent satellite reliability and launch schedule data approved in March 2009, the estimated long-term probability of maintaining a constellation of at least 24 operational satellites falls below 95 percent during fiscal year 2010 and remains below 95 percent until the end of fiscal year 2014, at times falling to about 80 percent."

Availability of Terminal Service



Terminal Area Service (HAL=1 NM)

Availability of Enroute Service



Enroute Service (HAL=2 NM)

Contact Info

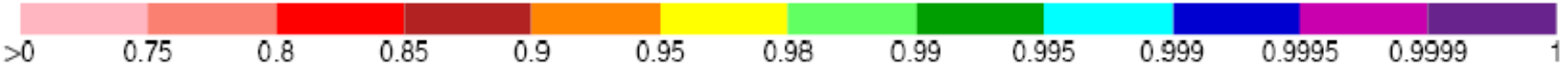
- Rick Niles
- fniles@mitre.org
- 703 983 7348

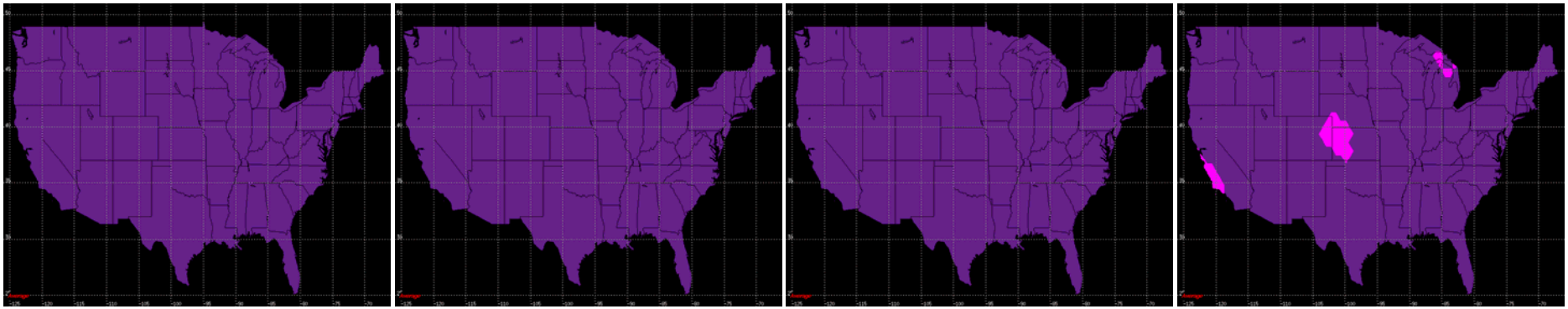
- Vince Massimini
- svm@mitre.org
- 703 983 5893

Backup Slides

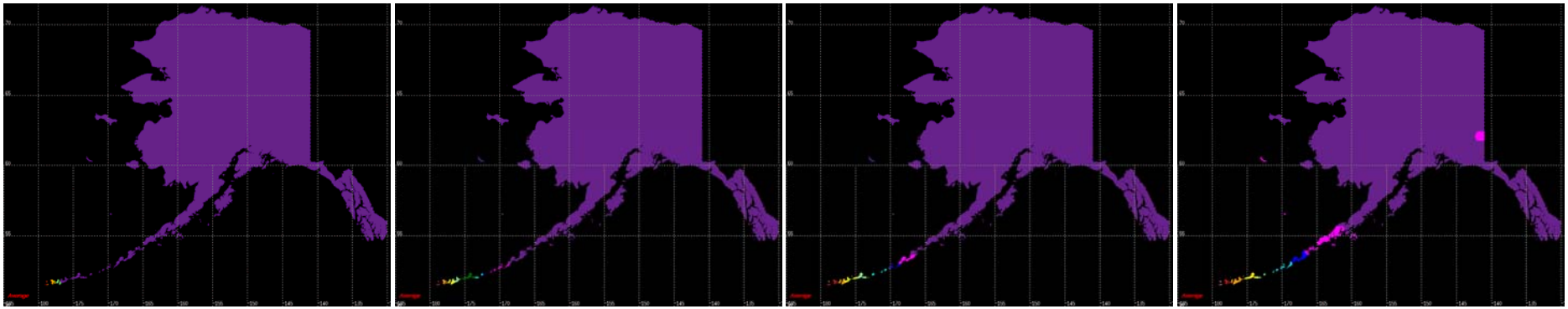
WAAS Reduced Availability

LNAV (0.3 NM) with Western GEO Message and Ranging





24, No Failures | **23 of 24, NF** | **22 of 24, NF** | **21 of 24, NF**



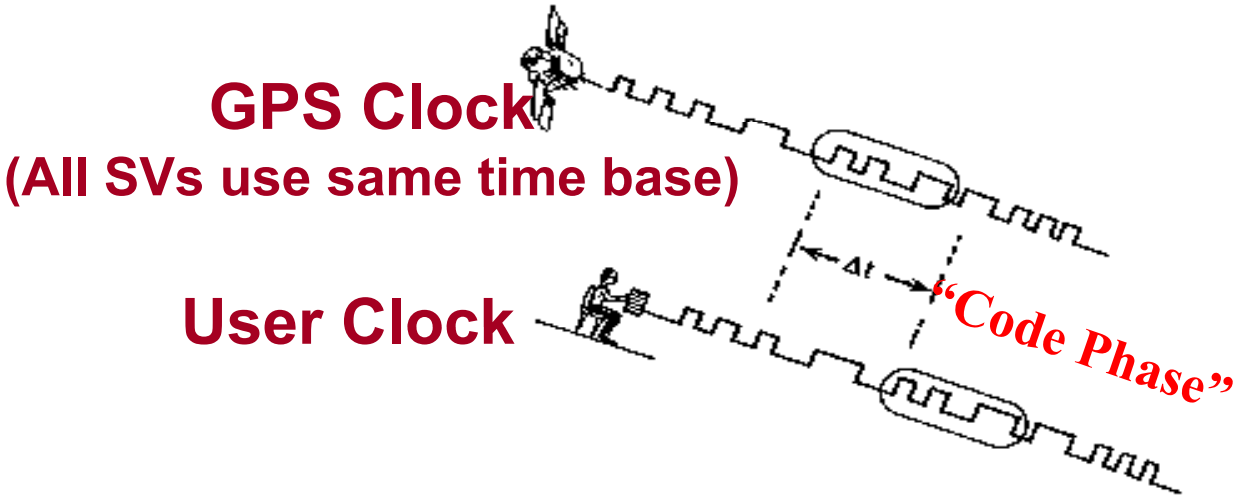
GEO @ 133 W, No GEO Failures

Current Positioning Systems

- **Standard Positioning Service (SPS)**
  - Single frequency receiver (L1)
  - C/A code and Nav/system data
- **Precise Positioning Service (PPS)**
  - Dual frequency receiver (L1 and L2)
    - Technical advantages to using two frequencies
  - C/A code, Nav/system data, and P(Y) code
  - Generally available to DOD and other approved users
  - Will not discuss further in this briefing

Range and Velocity Measurement (SPS)

- **Each SV has a different 1023 bit pseudo random (PRN) code from which the user can determine the time of transmission**
  - **Repeats each millisecond**
  - **Continuous/passive--not like DME or radar**
- **User velocity can be measured from Doppler shift or from sequential position measurements**



Position Measurement (Code Phase Tracking)

- **Four unknowns**
  - Latitude, longitude, altitude, receiver clock bias
- **Four SVs required for xyz solution: receiver clock bias is corrected by finding unique position solution**
  - SV time corrected for relativistic effects
  - Three SVs can give xy solution if altitude is known
- **Accurate time provided to user**