gAGE research group of Astronomy and Geomatics

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EGNOS TUTORIAL

Research **g**roup of **A**stronomy and **GE**omatics
(gAGE/UPC)

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Summary

- Part I: The EGNOS system
  - Augmentation Systems
  - EGNOS System Architecture
- Part II: Data Processing
  - SBAS Differential Corrections and Integrity
  - Performance
  - Examples
- Part III: EGNOS and Civil Aviation
  - Introduction to Civil Aviation Navigation
  - The EGNOS benefits

PART I

The EGNOS System

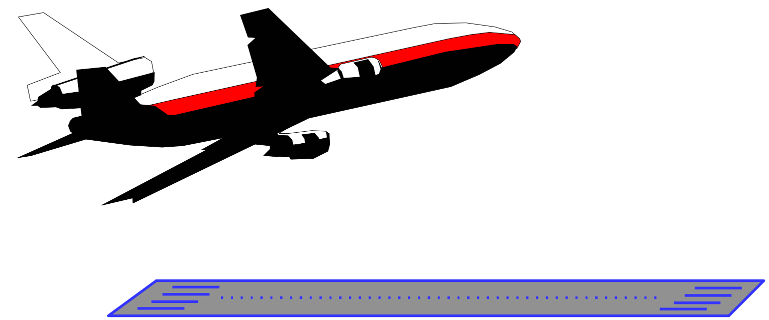
What Augmentation is?

- To enhance the performance of the current GNSS with additional information to:
  - Improve INTEGRITY via real-time monitoring
  - Improve ACCURACY via differential corrections
  - Improve AVAILABILITY and CONTINUITY

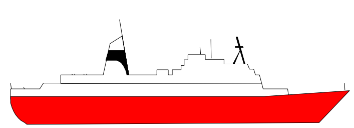
- Satellite Based Augmentation Systems (SBAS)
  - E.g., WAAS, **EGNOS**, MSAS
- Ground Based Augmentation Systems (GBAS)
  - E.g., LAAS
- Aircraft Based Augmentation (ABAS)
  - E.g., RAIM, Inertials, Baro Altimeter

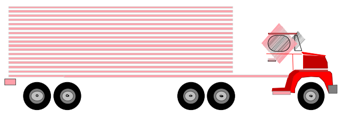
Why Augmentation Systems?

- Current GPS/GLONASS Navigation Systems cannot met the Requirements for All Phases of Flight:
  - Accuracy
  - Integrity
  - Continuity
  - Availability



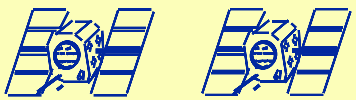
- Marine and land users will also require some sort of augmentation for improving the GPS/ GLONASS performances.



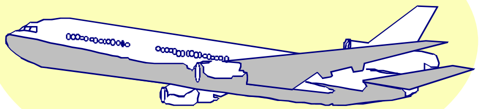


WHY GNSS NEEDS AN AUGMENTATION ?

GPS Only



Civil Aviation



PERFORMANCE | **CATEGORY I Requirements**

H. 13 m V. 22m	ACCURACY (95%)	H 16.0 m V 4.0 m
99% (RAIM)	AVAILABILITY	99% to 99.990%
?	INTEGRITY	2.10^{-7}/ approach Time to alarm 6 s
?	CONTINUITY OF SERVICE	10^{-5} / approach (10^{-6} / 15 s)

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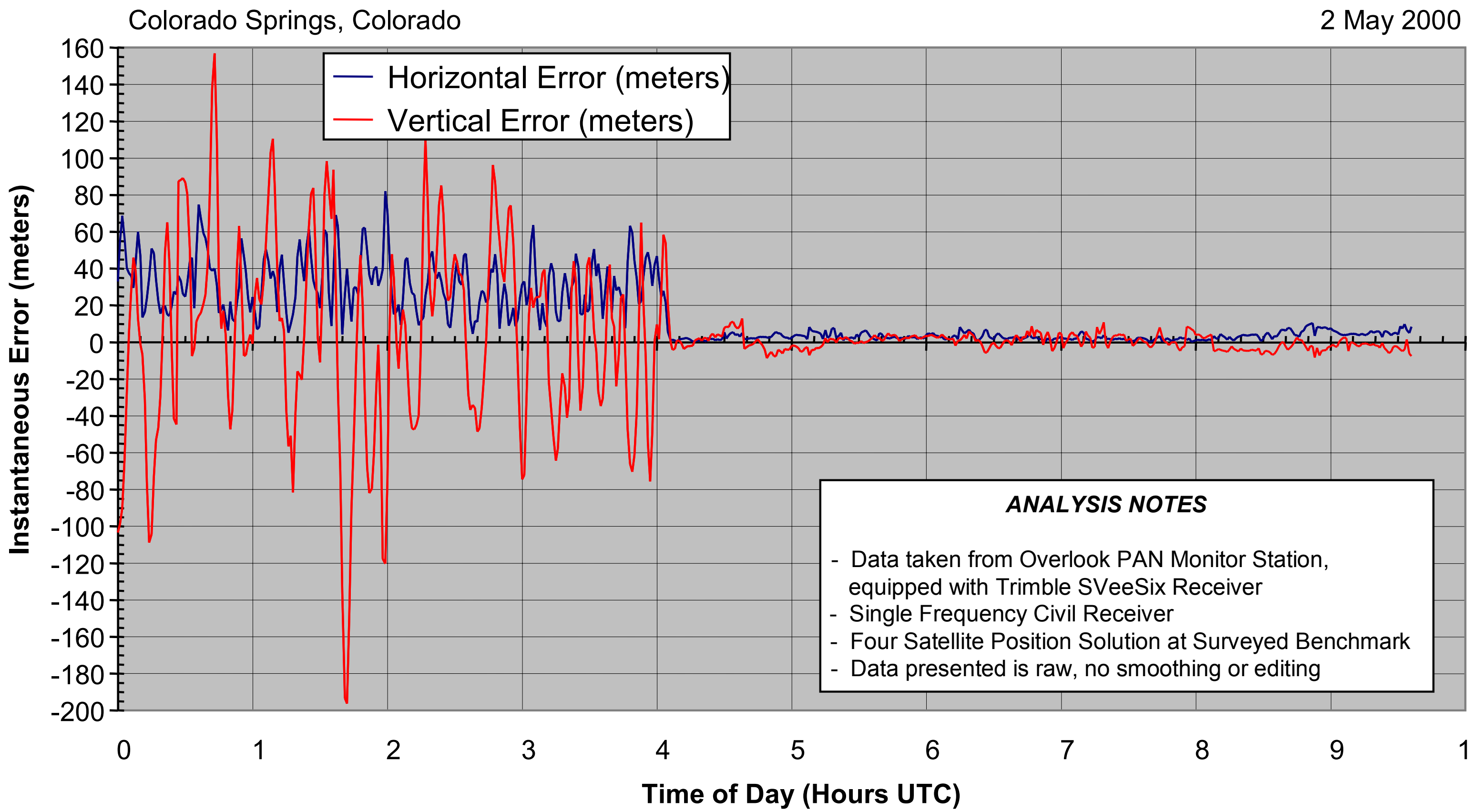
Accuracy: Difference between the measured position at any given time to the actual or true position.

Even with S/A off a Vertical Accuracy< 4m 95% of time cannot be achieved with standalone GPS.

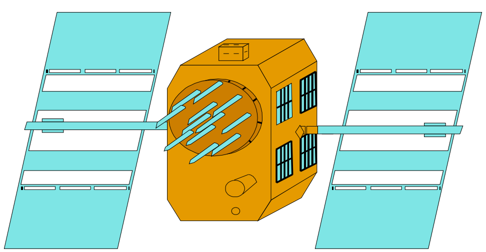


Integrity: Ability of a system to provide timely warnings to users or to shut itself down when it should not be used for navigation.

Standalone GPS and GLONAS Integrity is Not Guaranteed

GPS/GLONASS Satellites:

- Time to alarm is from minutes to hours
- No indication of quality of service



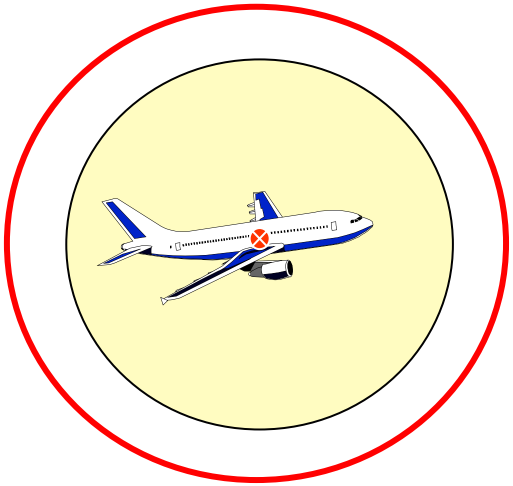
Health Messages:

- GPS up to 2 hours late
- GLONASS up to 16 hours late

Continuity: Ability of a system to perform its function without (unpredicted) interruptions during the intended operation.

Availability: Ability of a system to perform its function at initiation of intended operation. System availability is the percentage of time that accuracy, integrity and continuity requirements are met.

Availability and Continuity Must meet requirements



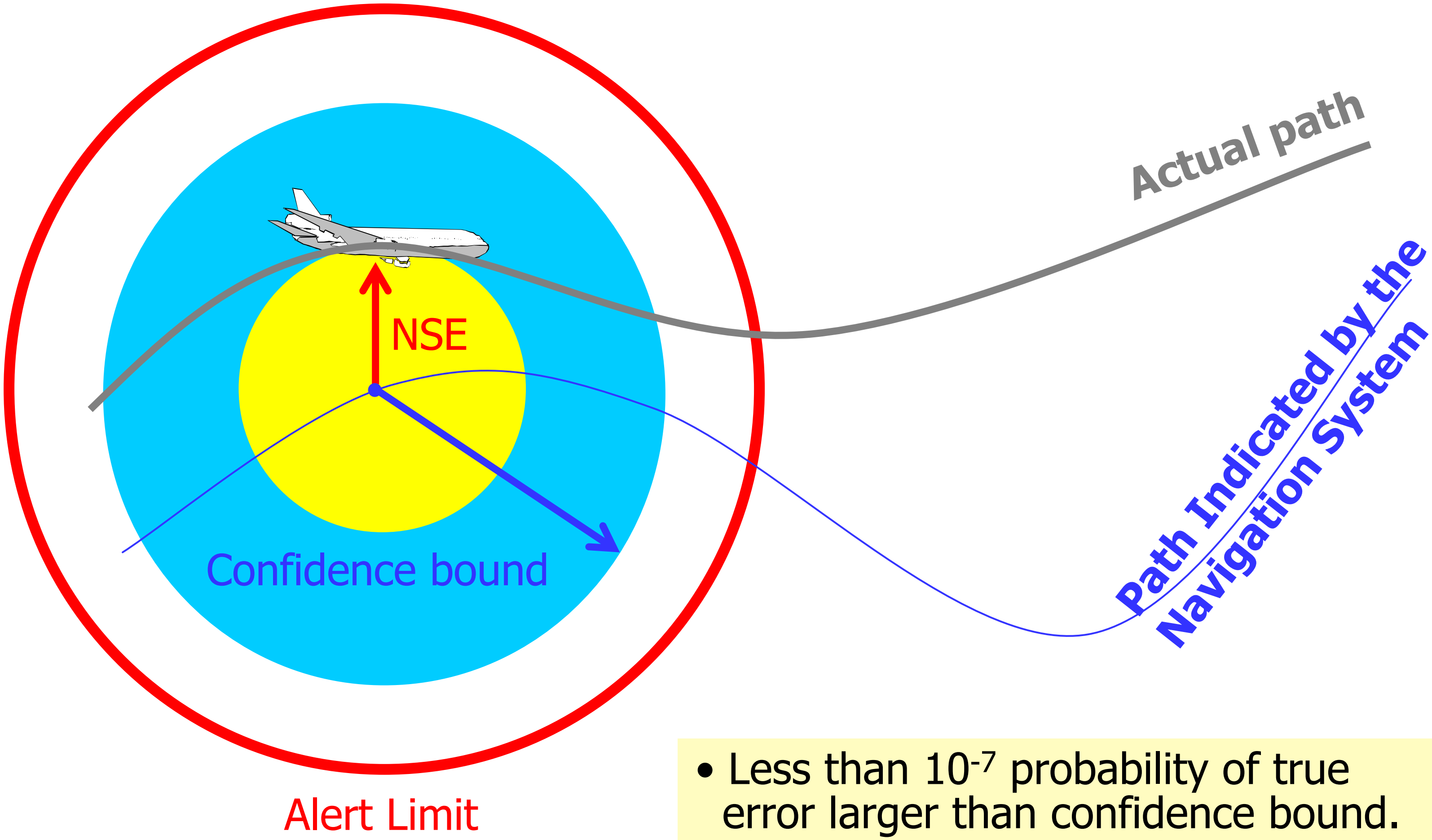
- Continuity:

  Less than 10^{-5} Chance of Aborting a Procedure Once it is Initiated.

- Availability:

  >99% for every phase of flight (SARPS).

INTEGRITY



- Less than 10^{-7} probability of true error larger than confidence bound.
- Time to alarm 6 s

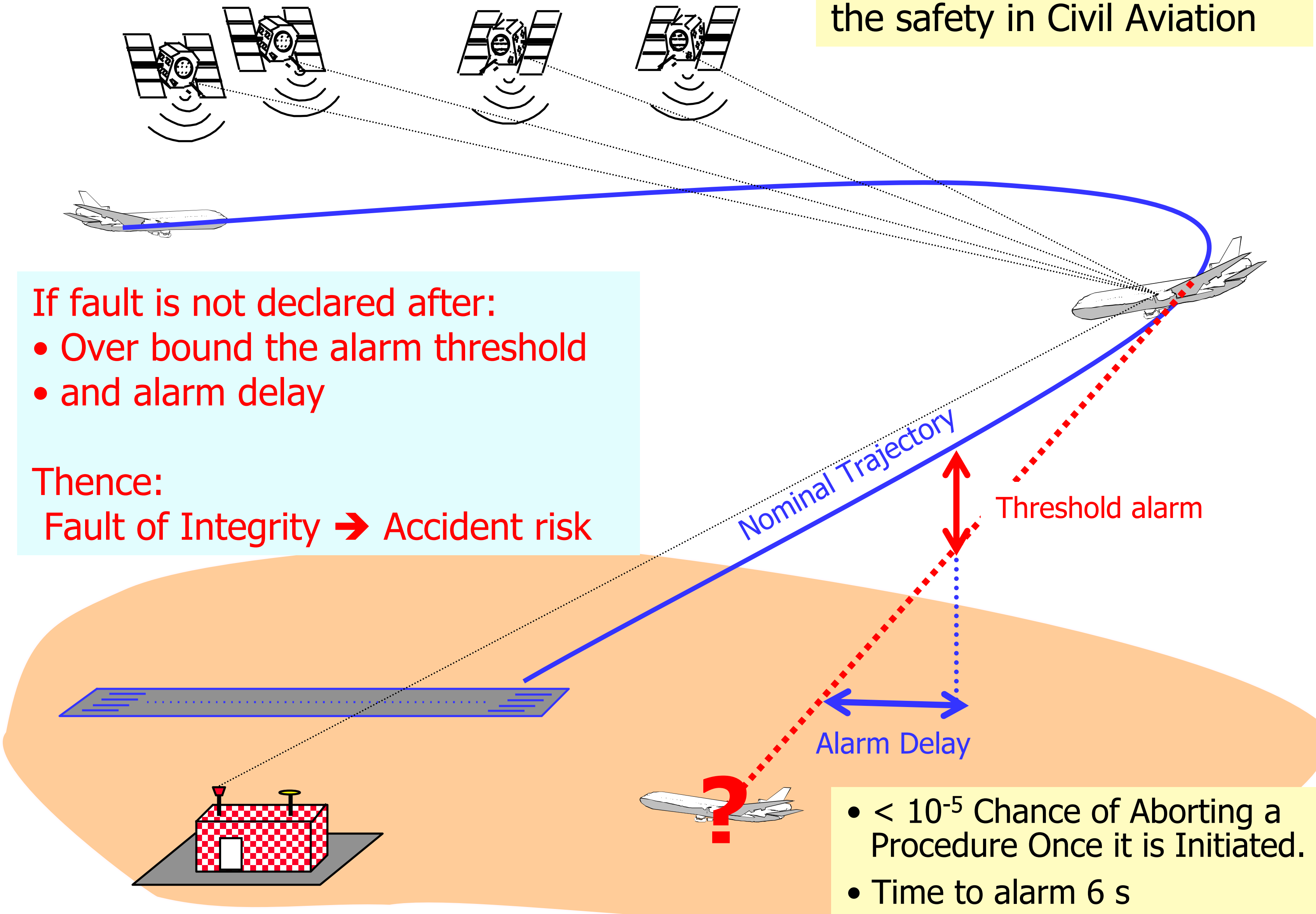
Strong Requirements for the safety in Civil Aviation

If fault is not declared after:

- Over bound the alarm threshold
- and alarm delay

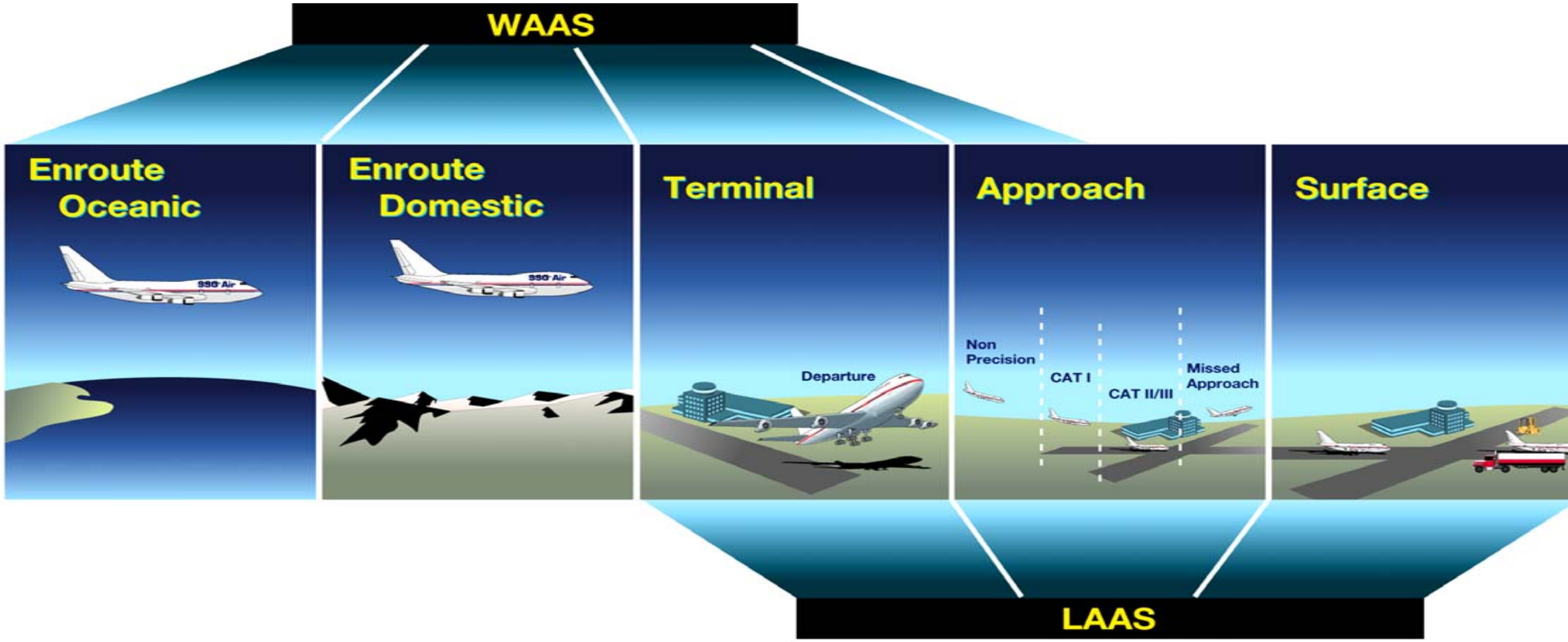
Thence:

Fault of Integrity ➔ Accident risk



- < 10^{-5} Chance of Aborting a Procedure Once it is Initiated.
- Time to alarm 6 s

SBAS and GBAS Navigation Modes



Aviation Signal-in-Space Performance Requirements

Aviation	Accuracy (H) 95%	Accuracy (V) 95%	Alert Limit (H)	Alert Limit (V)	Integrity	Time to alert	Continuity	Avail-ability
ENR	3.7 Km (2.0 NM)	N/A	7400 m 3700 m 1850 m	N/A	$1\text{-}10^{-7}$/h	5 min.	$1\text{-}10^{-4}$/h to $1\text{-}10^{-8}$/h	0.99 to 0.99999
TMA	0.74 Km (0.4 NM)	N/A	1850 m	N/A	$1\text{-}10^{-7}$/h	15 s	$1\text{-}10^{-4}$/h to $1\text{-}10^{-8}$/h	0.999 to 0.99999
NPA	220 m (720 ft)	N/A	600 m	N/A	1-10-7/h	10 s	1-10-4/h to 1-10-8/h	0.99 to 0.99999
APV-I	220 m (720 ft)	20 m (66 ft)	600 m	50 m	1-2x10-7 per approach	10 s	1-8x10-6 in any 15 s	0.99 to 0.99999
APV-II	16.0 m (52 ft)	8.0 m (26 ft)	40 m	20 m	1-2x10-7 per approach	6 s	1-8x10-6 in any 15 s	0.99 to 0.99999
CAT-I	16.0 m (52 ft)	6.0 - 4.0 m (20 to 13 ft)	40 m	15 -10 m	1-2x10-7 per approach	6 s	1-8x10-6 in any 15 s	0.99 to 0.99999

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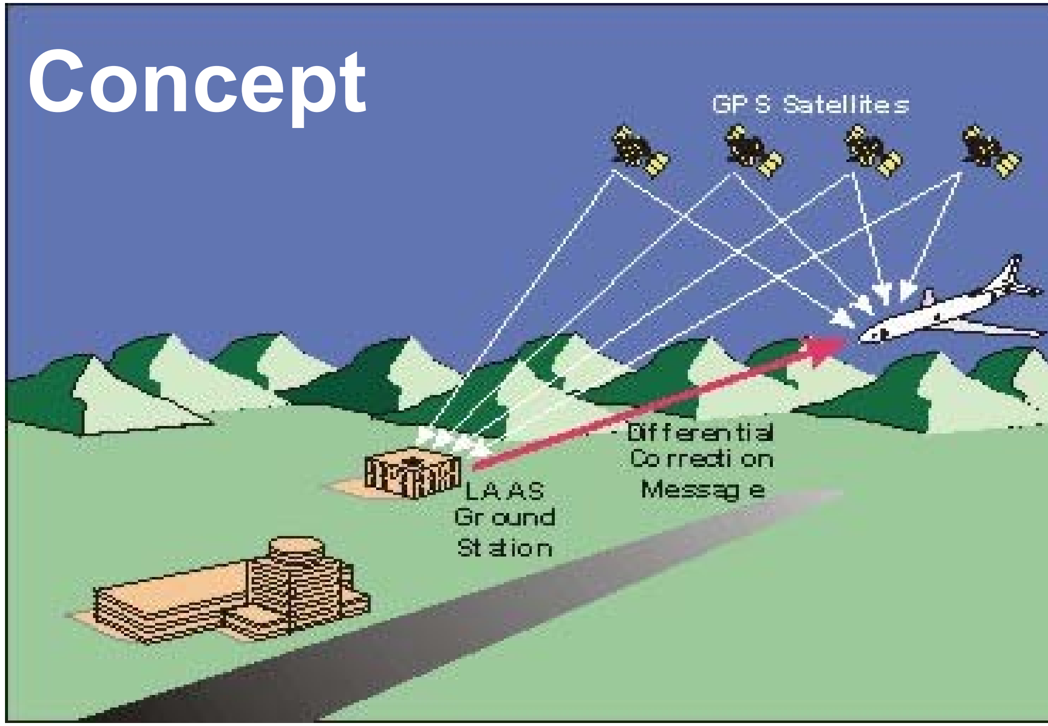
Maritime Signal-in-Space Performance Requirements

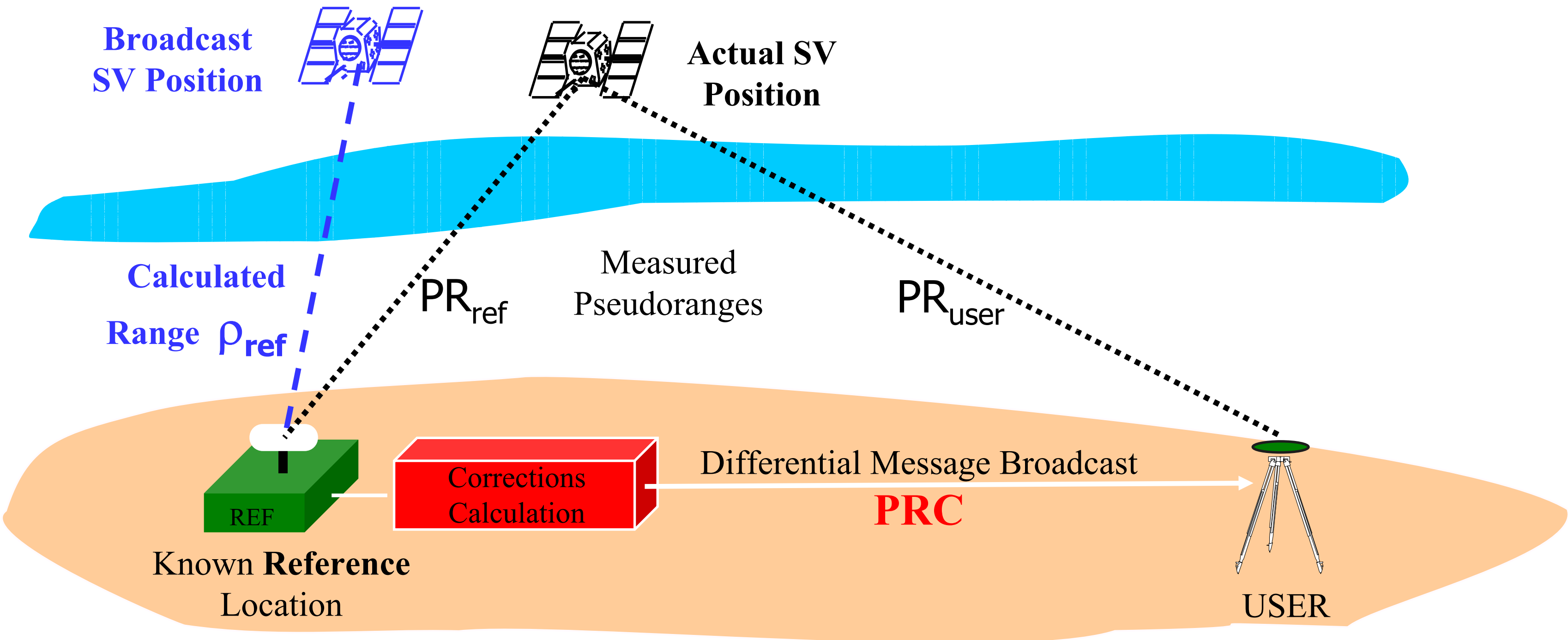
Maritime	Accuracy (H) 95%	Alert Limit (H)	Time to alert	Integrity risk (per 3 hours)
Ocean	10m	25m	10sec	10^{-5}
Costal	10m	25m	10 s	10^{-5}
Port approach and restricted waters	10m	25m	10 s	10^{-5}
Port	1m	2.5m	10 s	10^{-5}
Inland waterways	10m	25m	10 s	10^{-5}

GBAS Concept

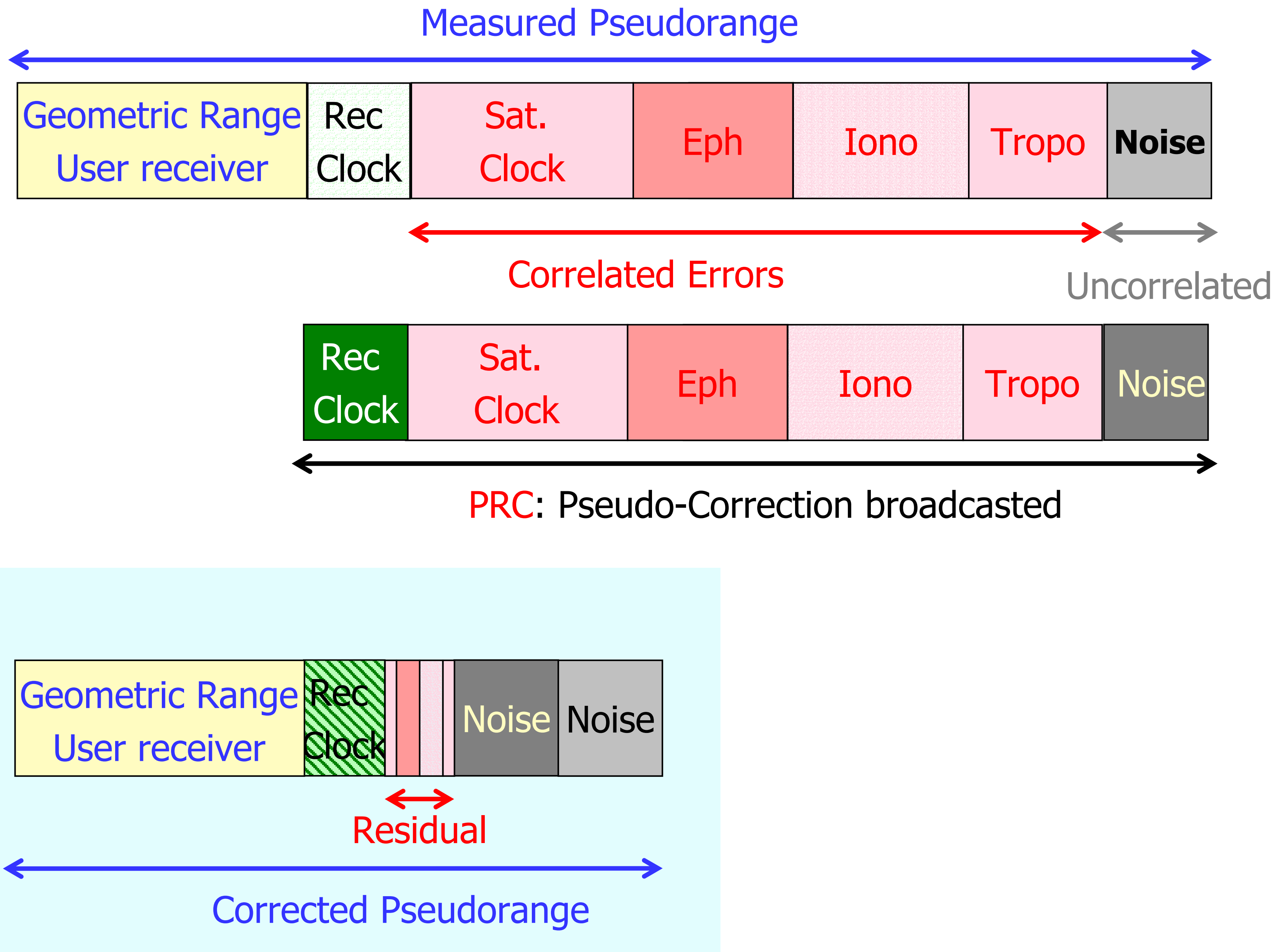


- Most of the measurement errors are common:
  clock, ephemeris, ionosphere and troposphere.
- A common correction valid for any receiver within the LADGPS area is generated and broadcast.
- The accuracy is limited by the spatial decorrelation of those error sources (1m at 100Km).

Differential Correction Calculation



- The first receiver in a reference station can calculate these errors knowing its exact location (corrections "PRC" calculated by the GBAS ground station): $PRC = PR_{ref} - \rho_{ref}$
- The second receiver (the user) will use these corrections to correct its own measurements and increase the accuracy of these measurements: $PR_{user} - PRC$


Measured Pseudorange
Geometric Range User receiver
Rec Clock
Sat. Clock
Eph
Iono
Tropo
Noise
Correlated Errors
Uncorrelated
Rec Clock
Sat. Clock
Eph
Iono
Tropo
Noise
PRC: Pseudo-Correction broadcasted
Geometric Range User receiver
Rec Clock
Noise
Noise
Residual
Corrected Pseudorange

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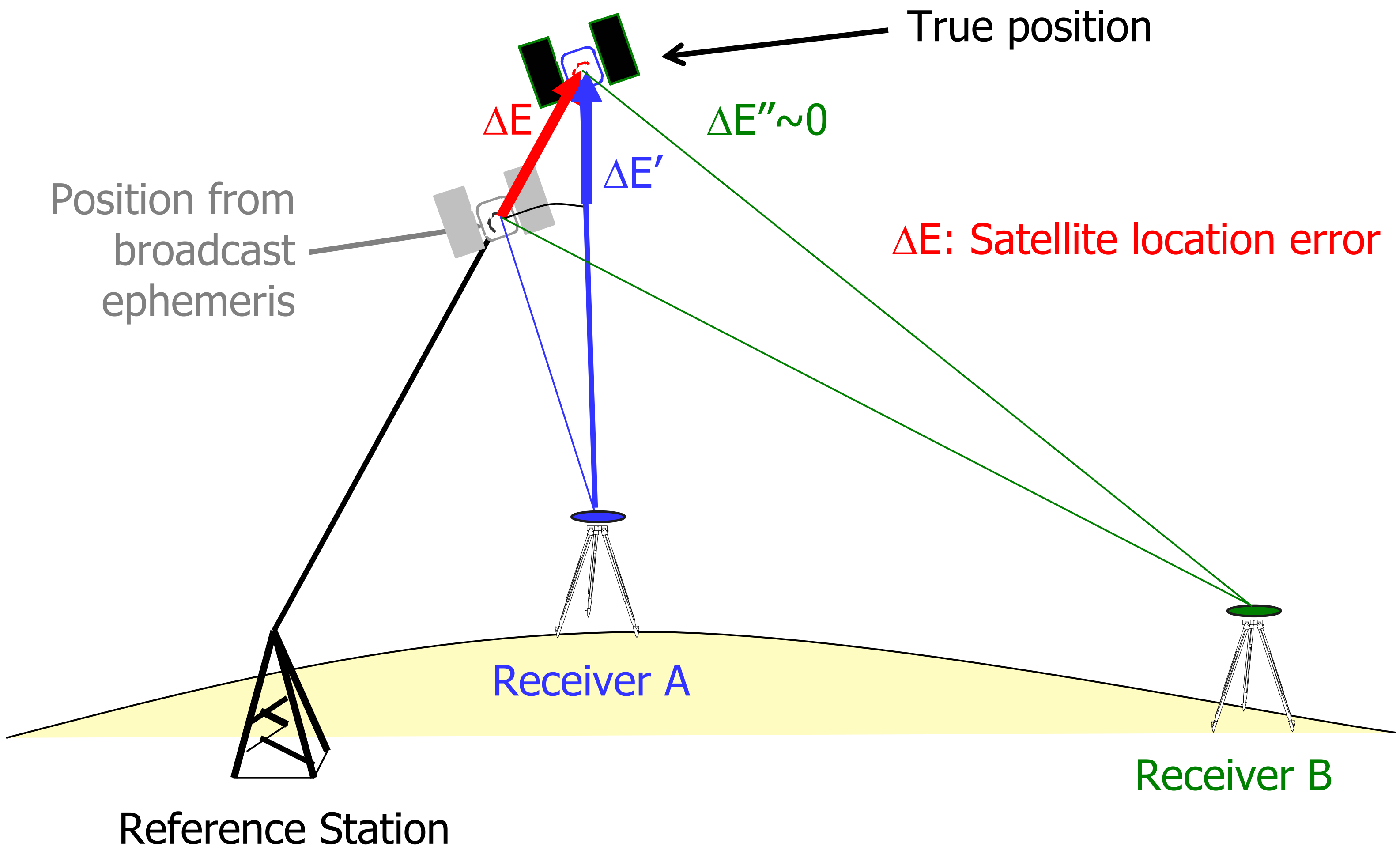
ERORS on the Signal

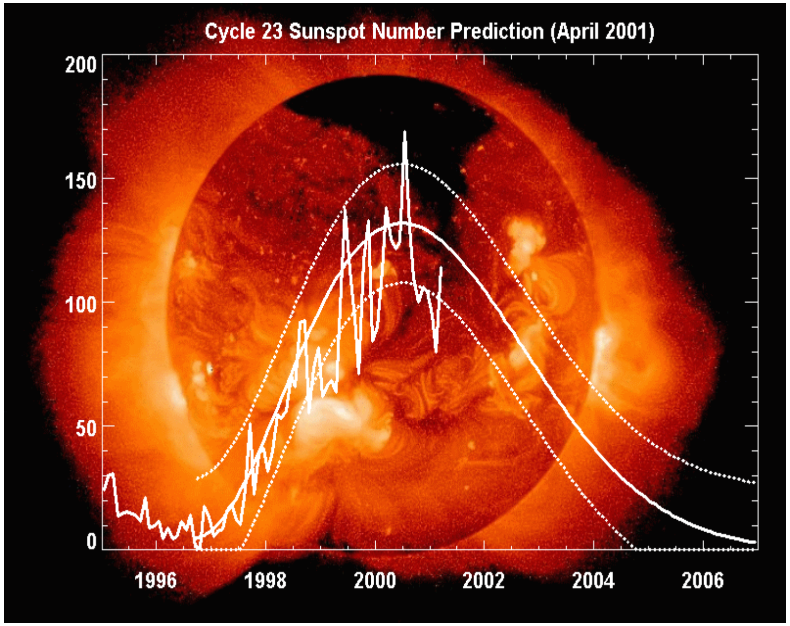
- Space Segment Errors:
  - Clock errors — Common
  - Ephemeris errors
- Propagation Errors
  - Ionospheric delay
  - Tropospheric delay — Weak spatial correlation
- Local Errors
  - Multipath
  - Receiver noise

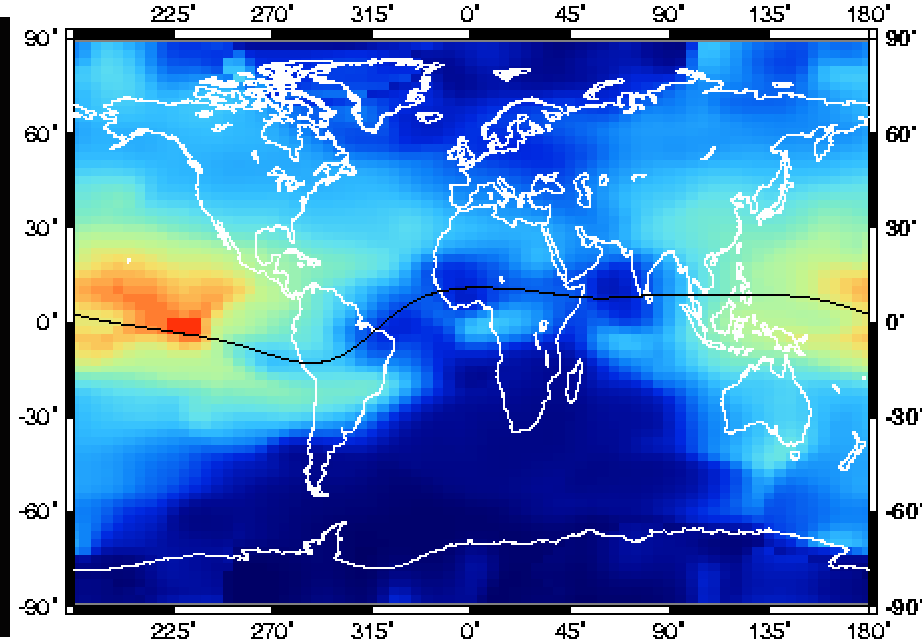
Ephemeris errors, Ionospheric delay → Strong spatial correlation

Multipath, Receiver noise → No spatial correlation

LADGPS Ephemeris Correction Errors due to the Geographic Separation

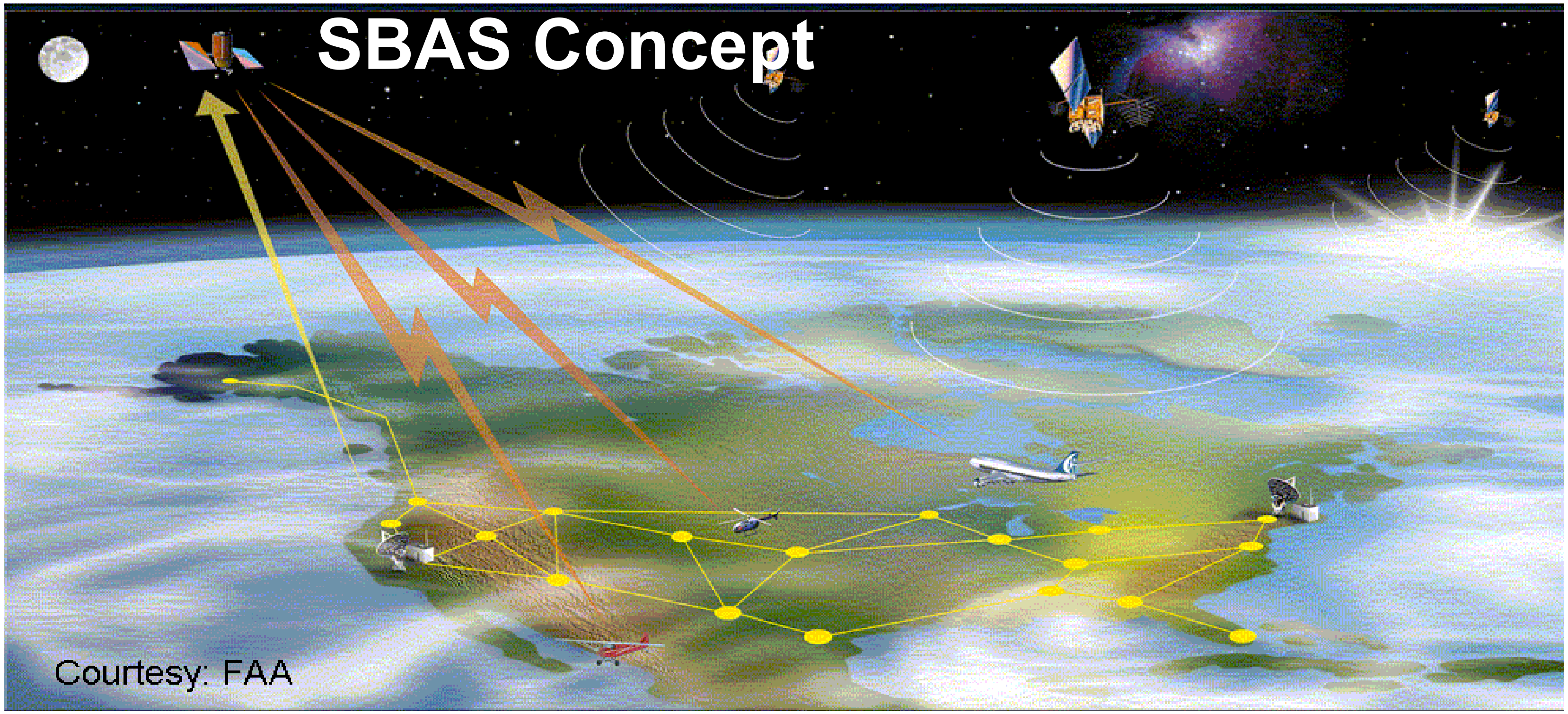






With SA set to Zero, the dominant error is now the error associated with the Ionosphere.

- **The ionosphere can add a significant amount of error to a user's position solution**
- **Based on several factors:**
  - **geographic location**
  - **time of day**
  - **time with respect to the solar cycle (11 years).**



The pseurorange error is split in its components.

- Clock error
- Ephemeris error
- Ionospheric error
- Local errors (troposphere, multipath, receiver noise)

Uses a network of receivers to cover broad geographic area

Error Mitigation

Error component	GBAS	SBAS
Satellite clock	Common Mode Differencing	Estimation and Removal each error component
Ephemeris		
Ionosphere		
Troposphere		Fixed Model
Multipath and Receiver Noise	Carrier Smoothing by user	

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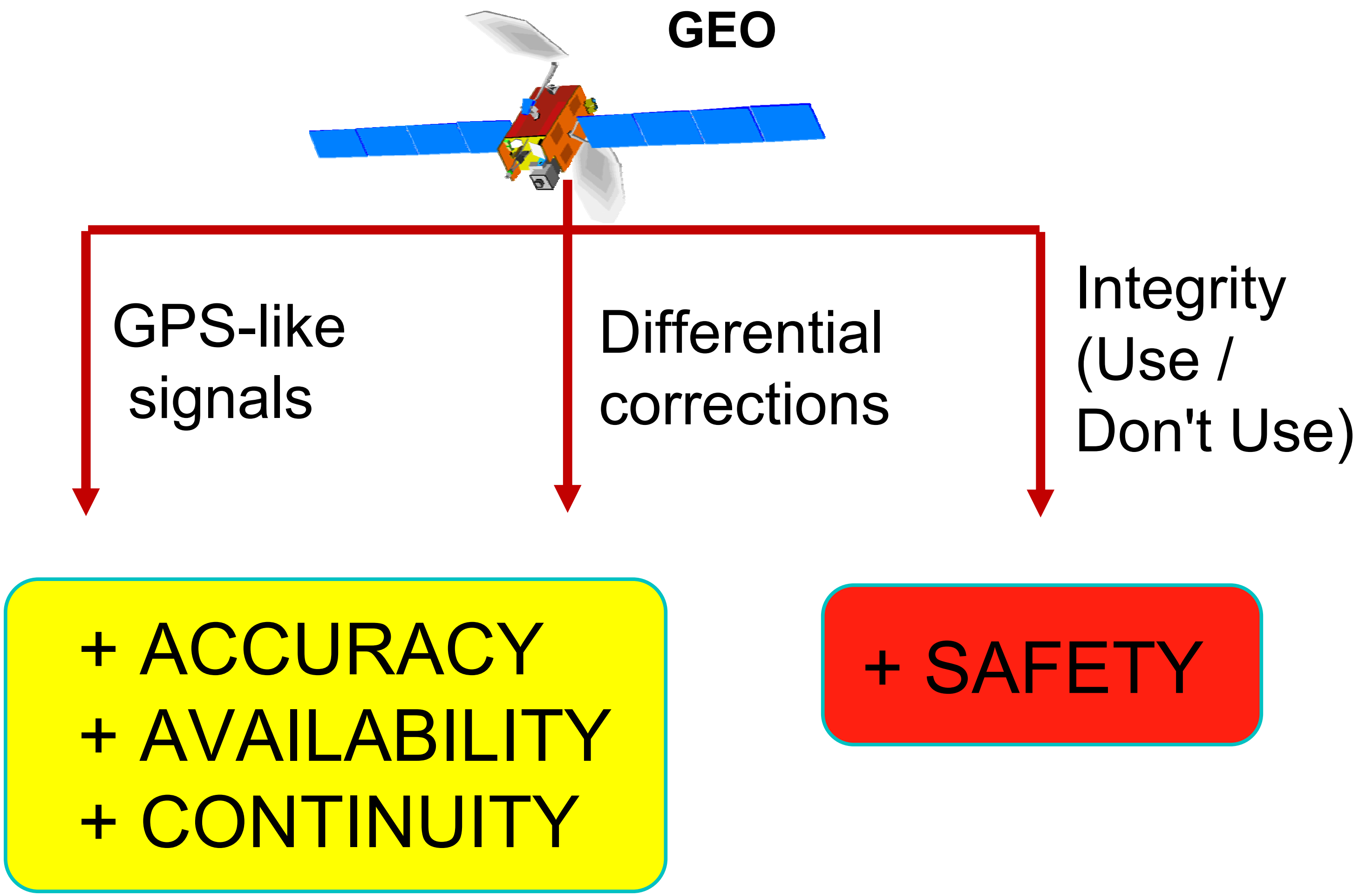
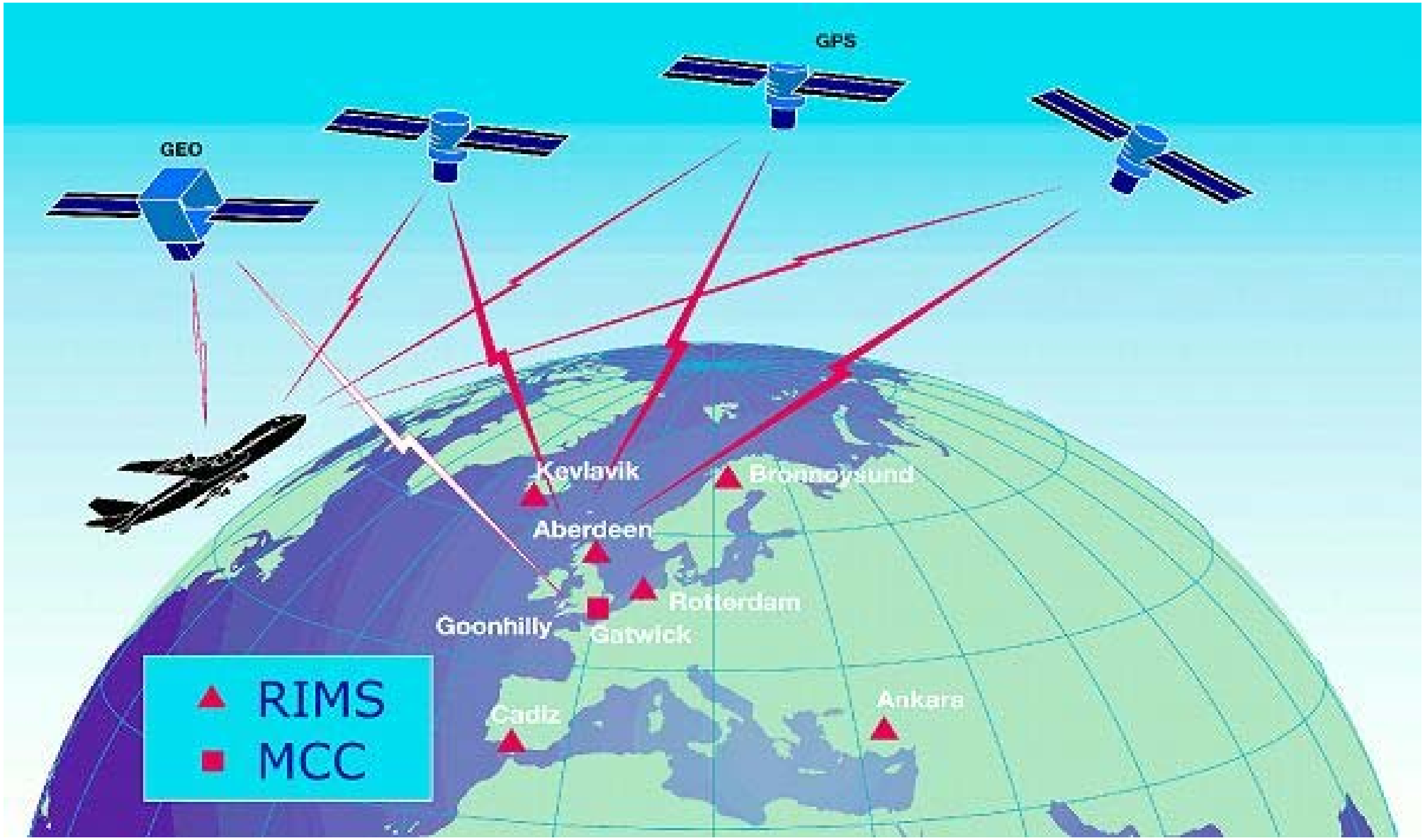


The European Geoestationary Navigation Overlay SERVICE (EGNOS)

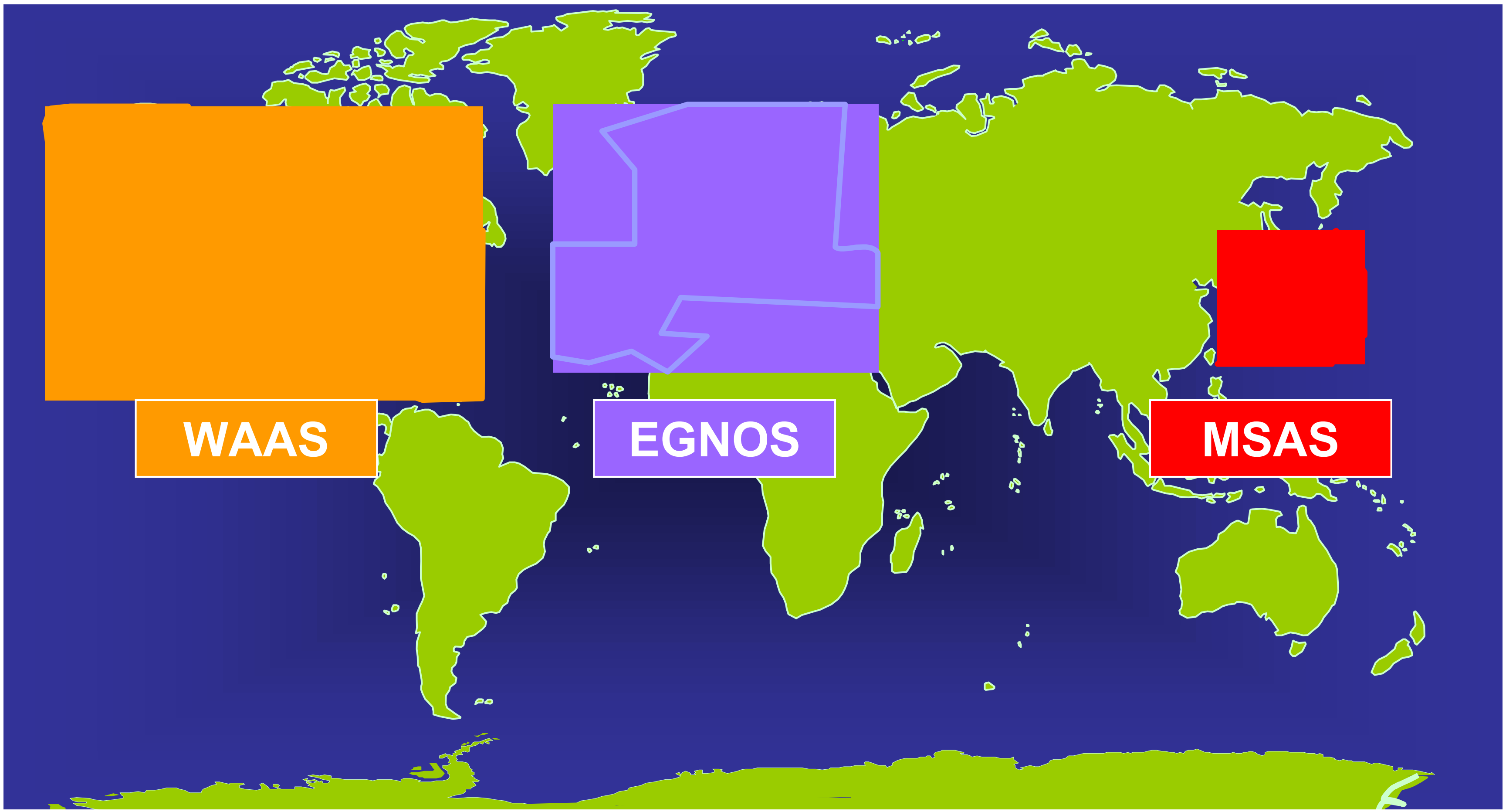


What EGNOS is?

- EGNOS is the European component of a Satellite Based Augmentation to GPS and GLONAS.

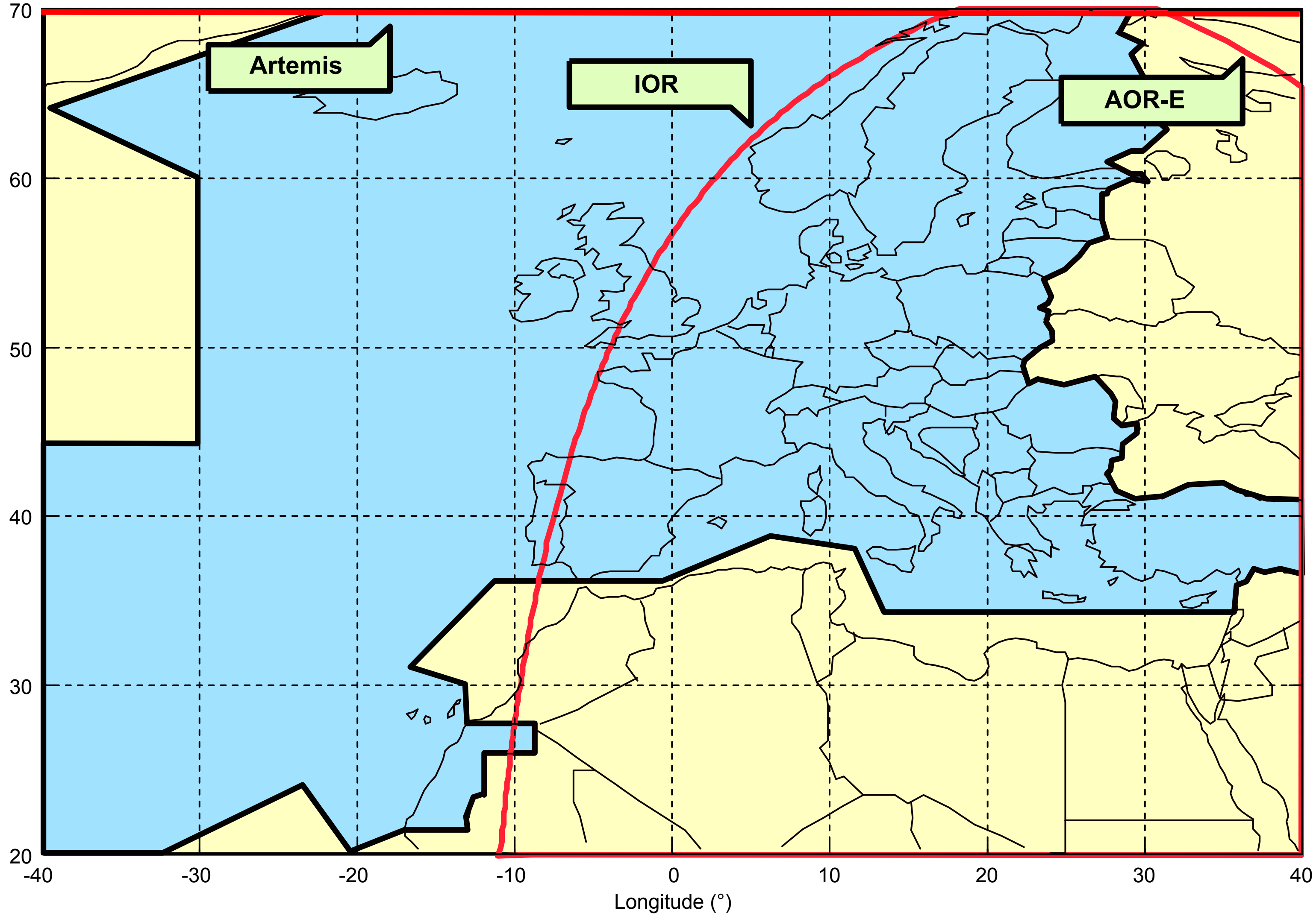
- EGNOS is being developed under the responsibility of a tripartite group:
  - The European Space Agency (ESA)
  - The European Organization for the Safety of Air Navigation (EUROCONTROL)
  - The Commission of the European Union.

Three existing SBAS Systems



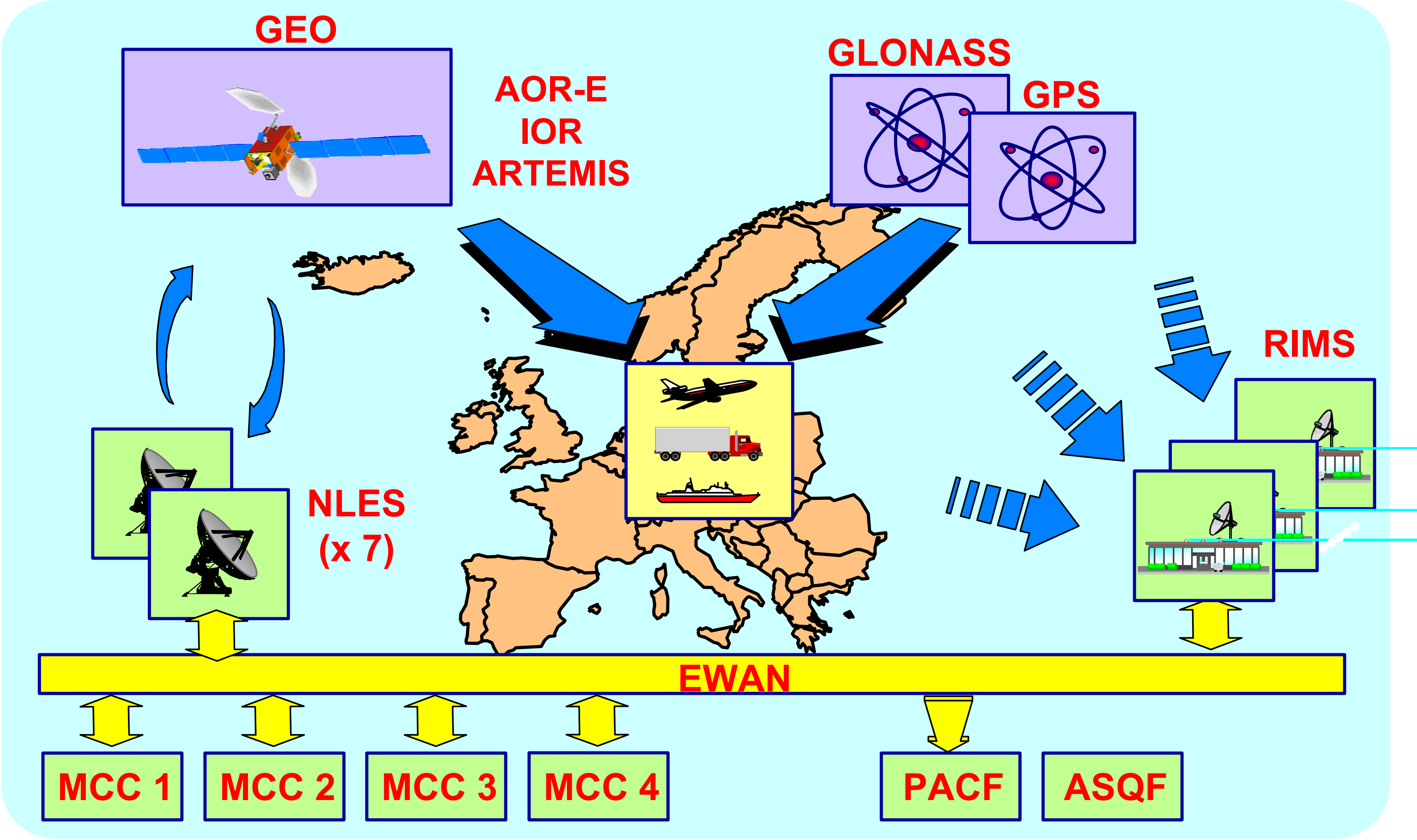
ECAC Area

(ECAC: European Civil Aviation Conference)

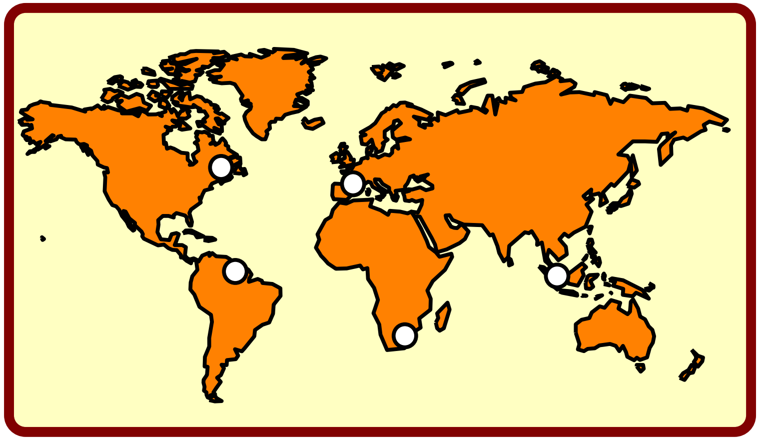


EGNOS AOC Architecture

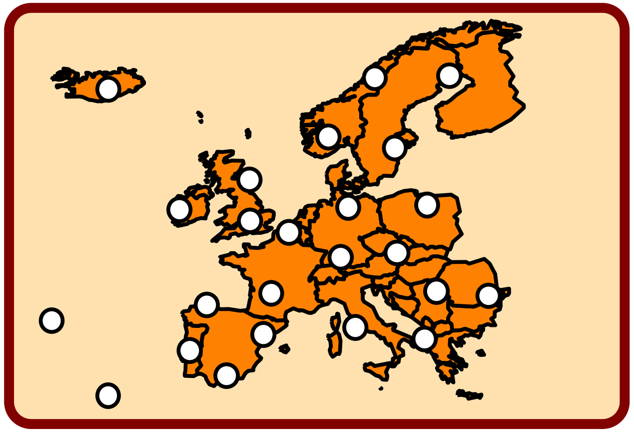
(AOC: Avanced Operational Capability)



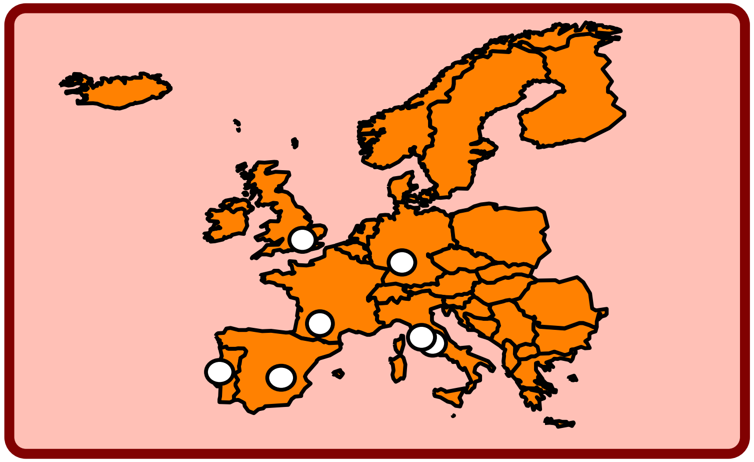
EGNOS AOC GROUND NETWORK TOPOLOGY



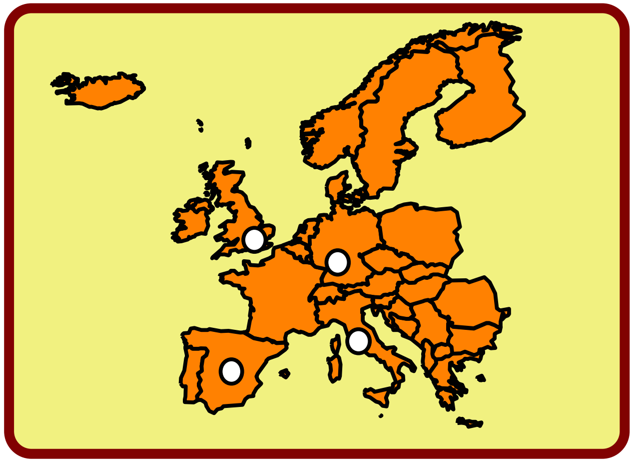
RIMS for a good GEO RANGING



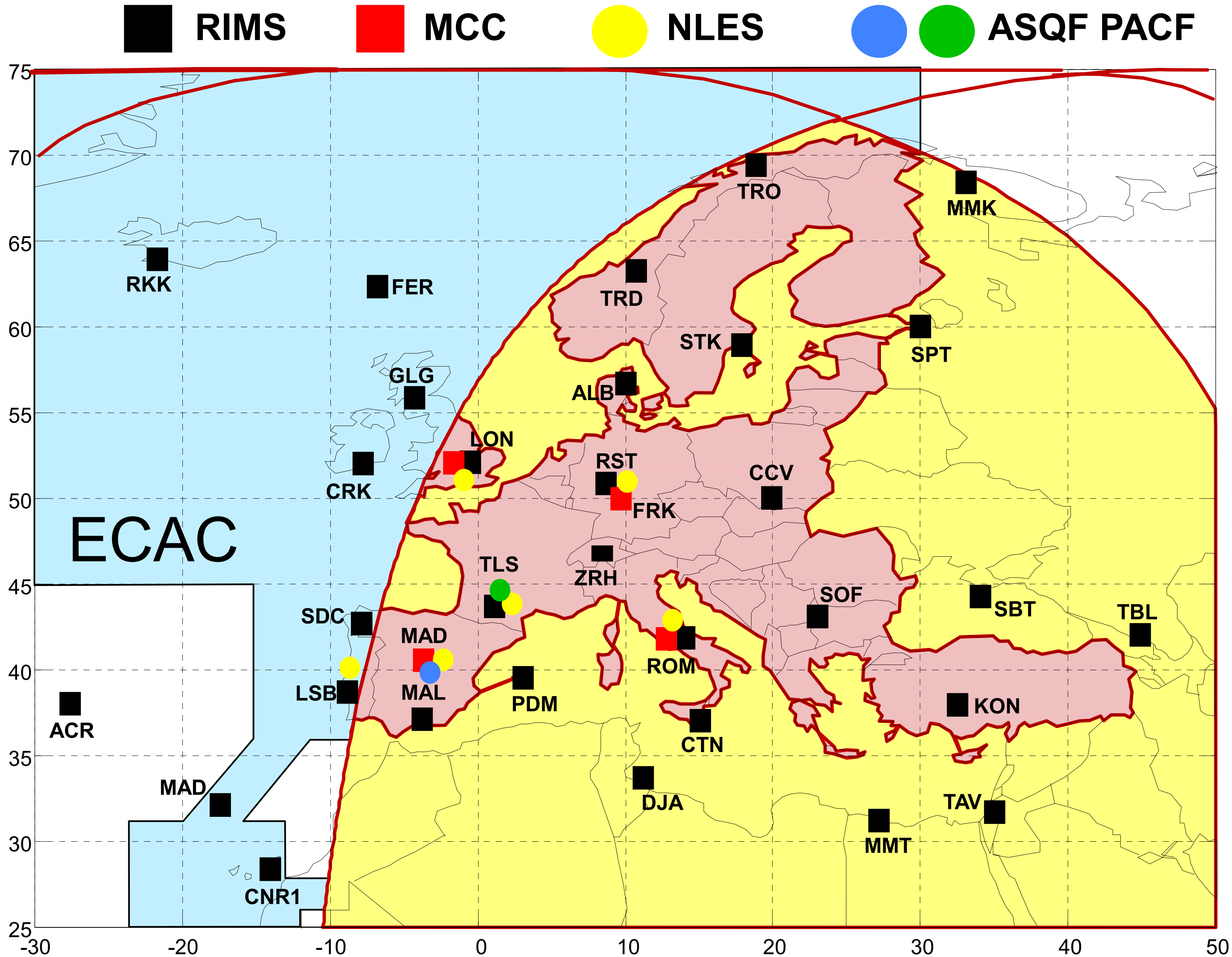
RIMS in ECAC



NLES



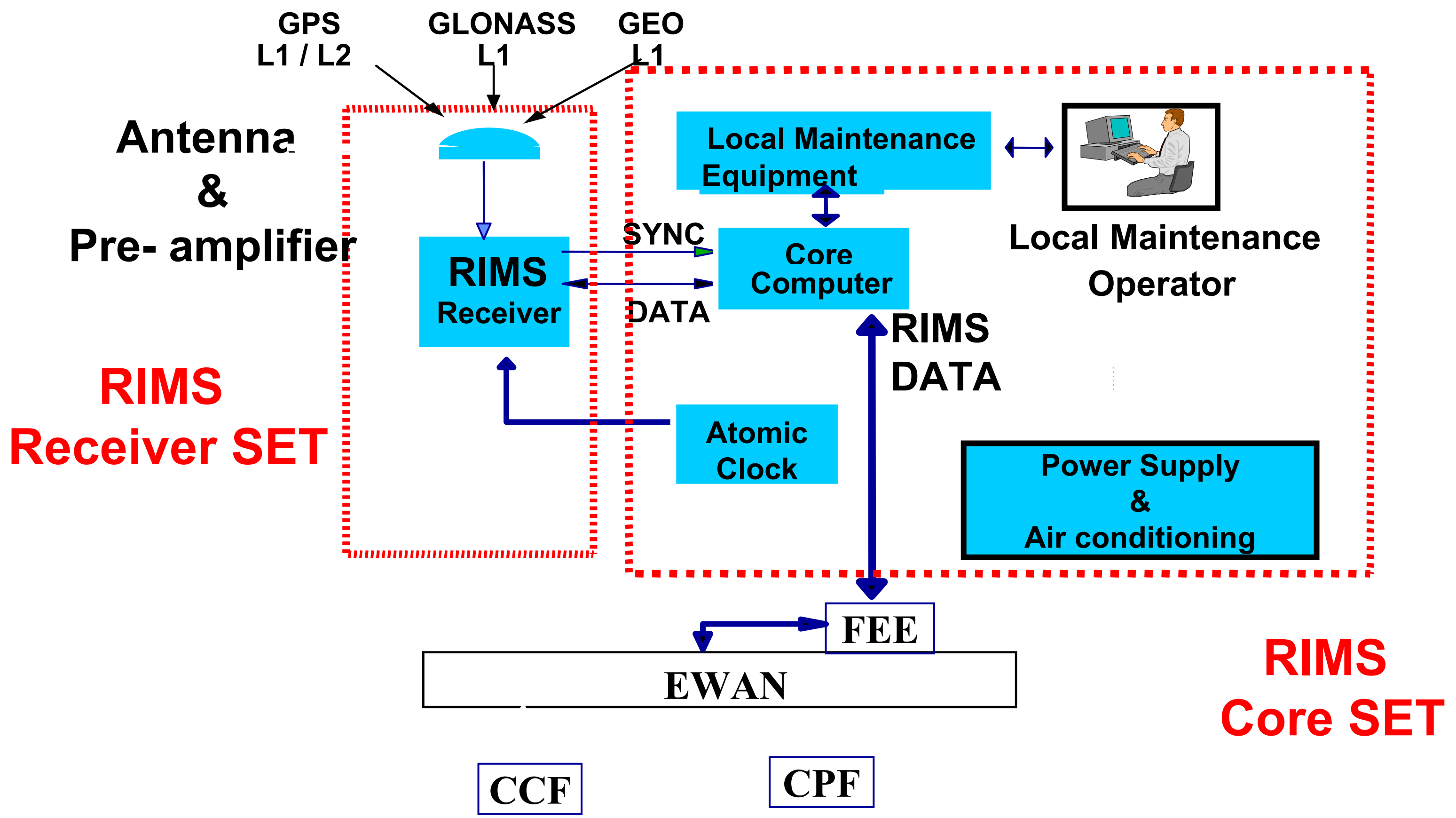
MCCs



Manuel Hernández-Pajares, J. Miguel Juan, Jaume Sanz, Xavier Prats, February 2002.

Ranging & Integrity Monitoring Station (RIMS)

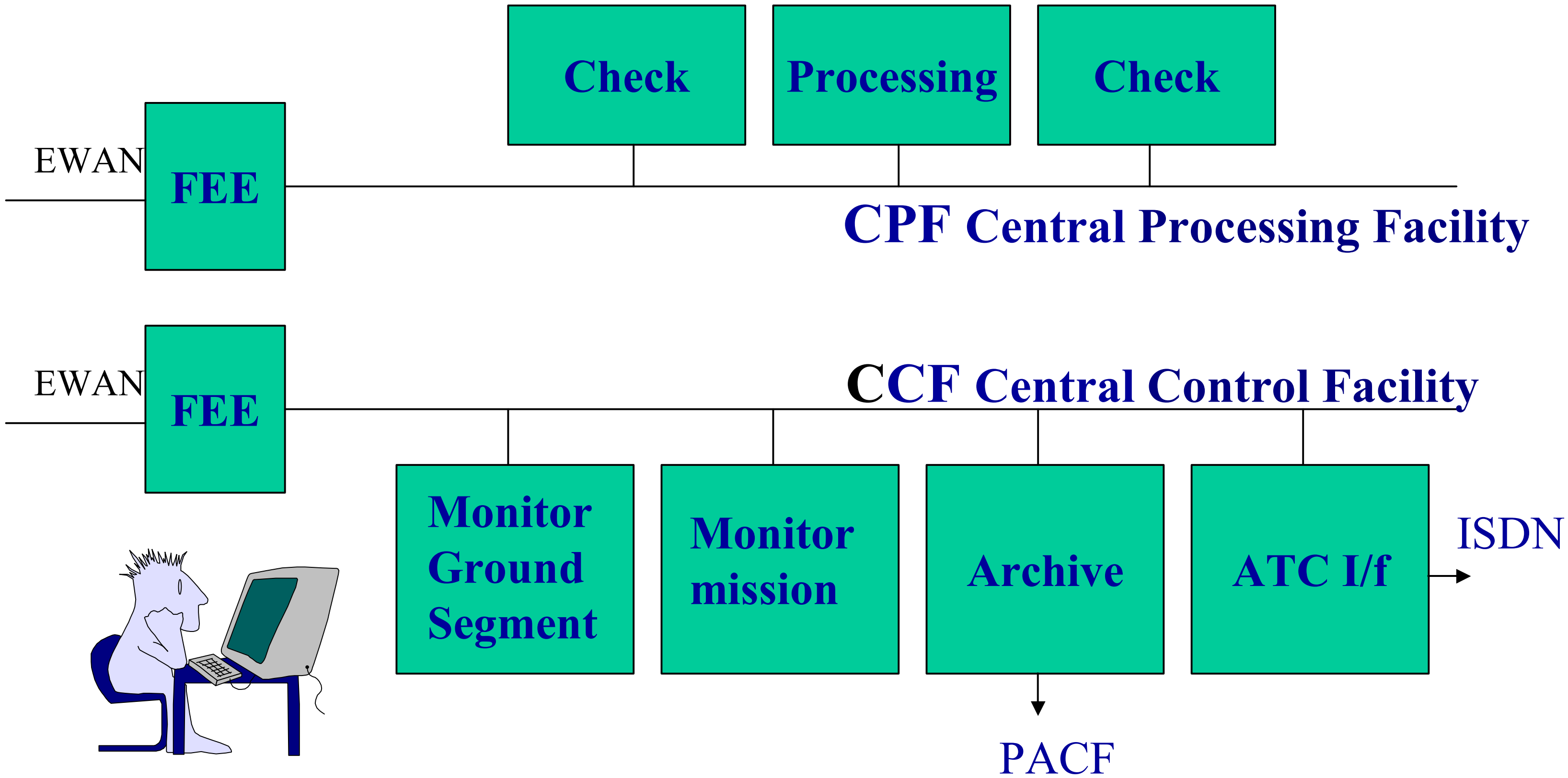
33 RIMS in EGNOS +1 specific RIMS for UTC time



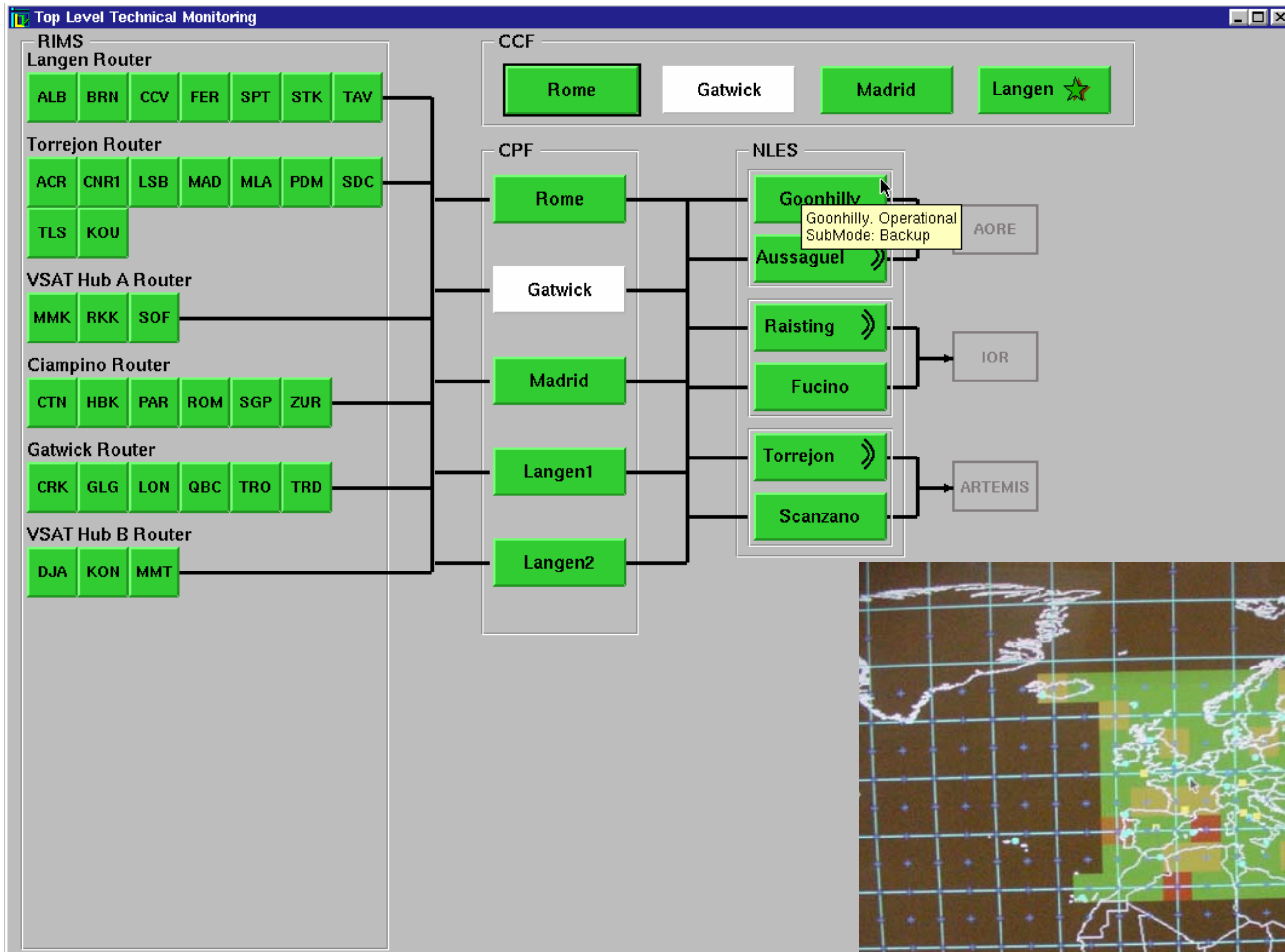
Master Control Center (MCC)

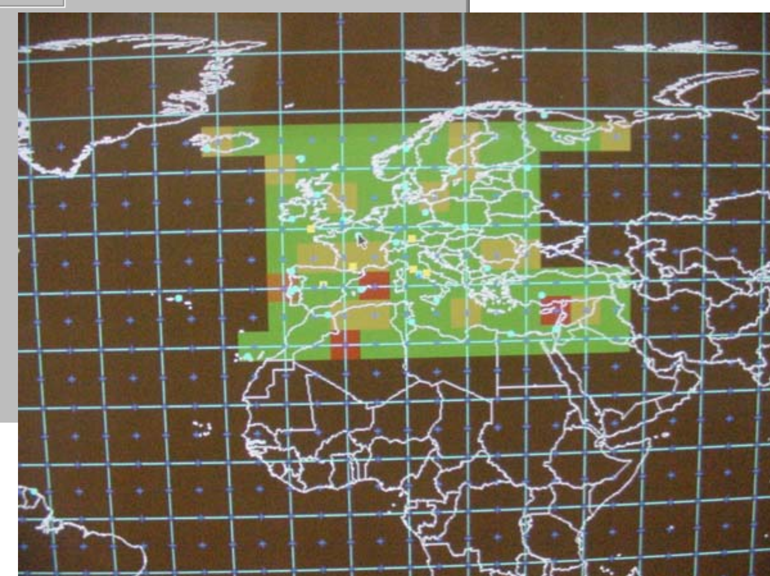
- MCC is Subdivided into
  - CCF (Central Control Facility)
    - Monitoring and control EGNOS G/S
    - Mission Monitoring and archive
    - ATC I/F
  - CPF (Central Processing Facility)
    - Provides EGNOS WAD corrections
    - Ensures the Integrity of the EGNOS users
    - Utilises independent RIMS channels for checking of corrections
    - Real time software system developed to high software standards
- 4 MCCs will be implemented in EGNOS

Master Control Center (MCC)



CCF VIEWS



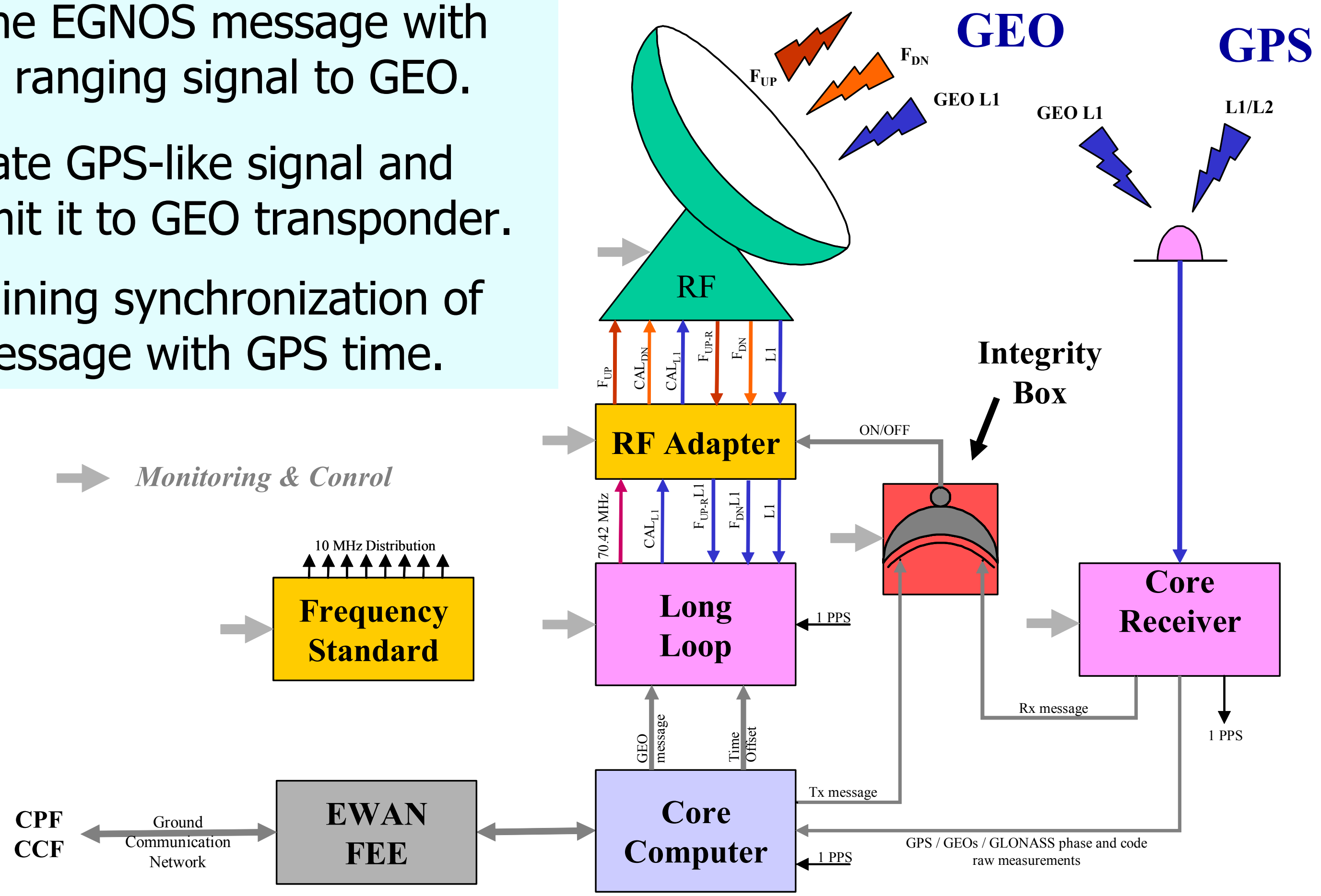


CCF: Global Accuracy display

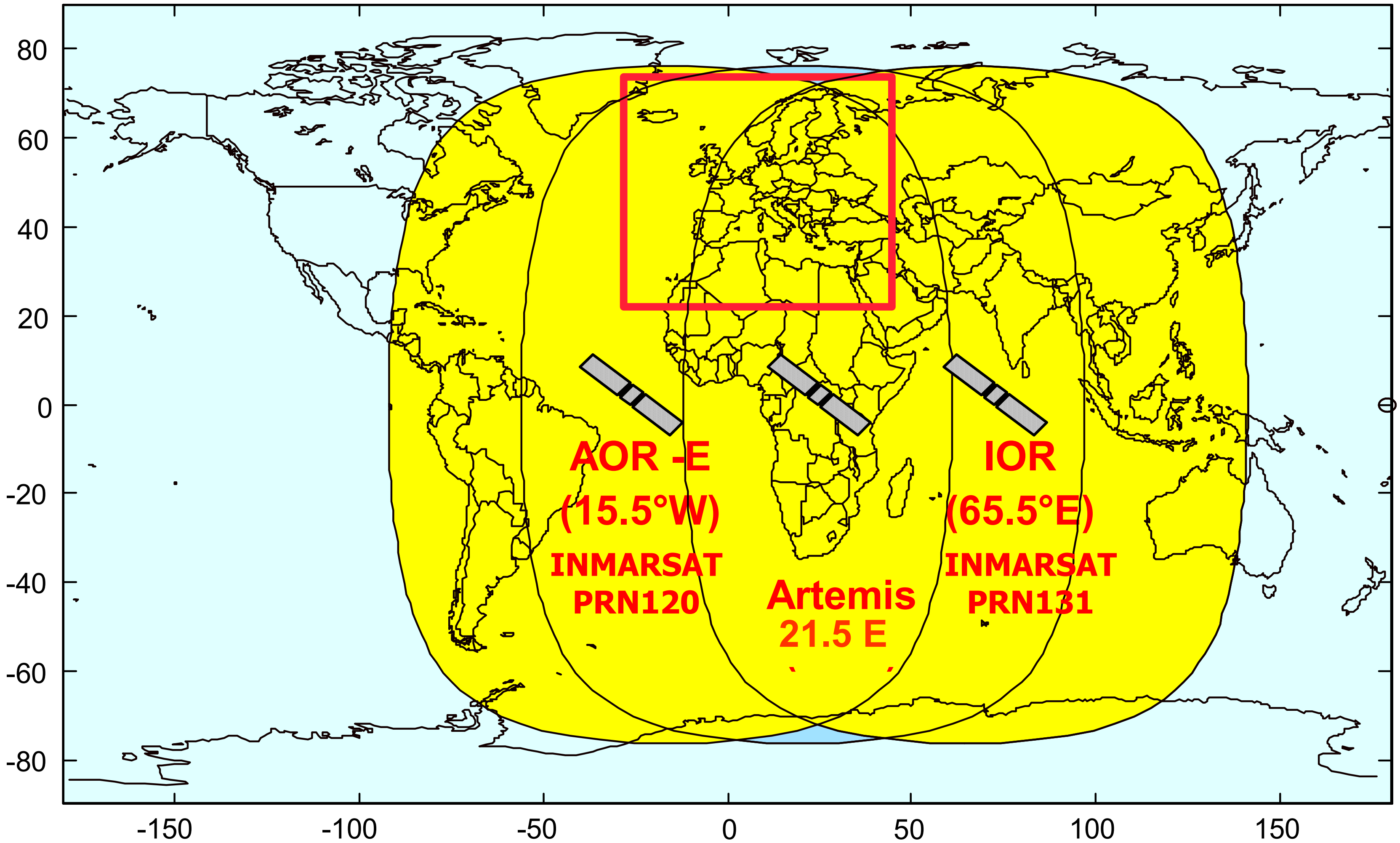
Navigation Land Earth Station (NLES)

Uplink the EGNOS message with the GEO ranging signal to GEO.

- Generate GPS-like signal and transmit it to GEO transponder.
- Maintaining synchronization of the message with GPS time.



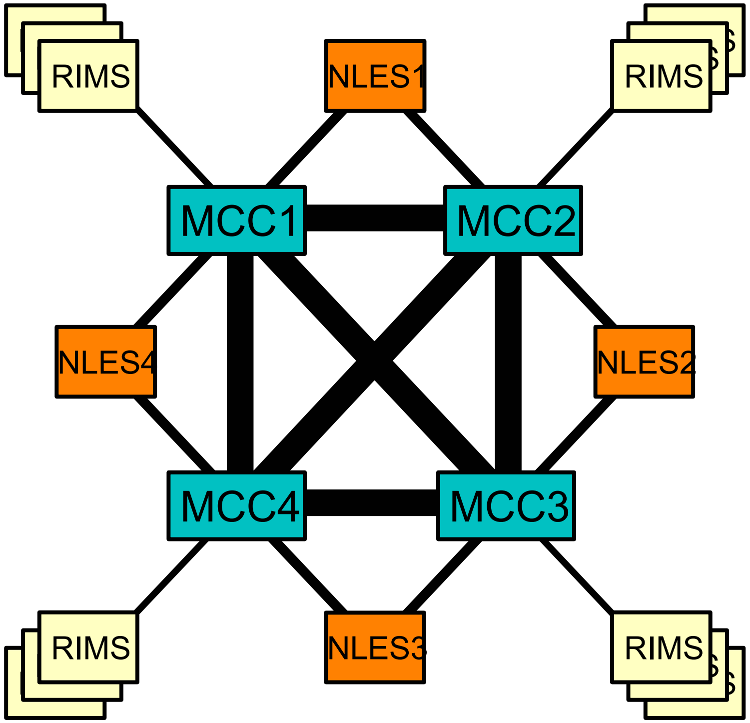
Geostationary satellite Broadcast Areas (GBA)



Manuel Hernández-Pajares, J. Miguel Juan, Jaume Sanz, Xavier Prats, February 2002.

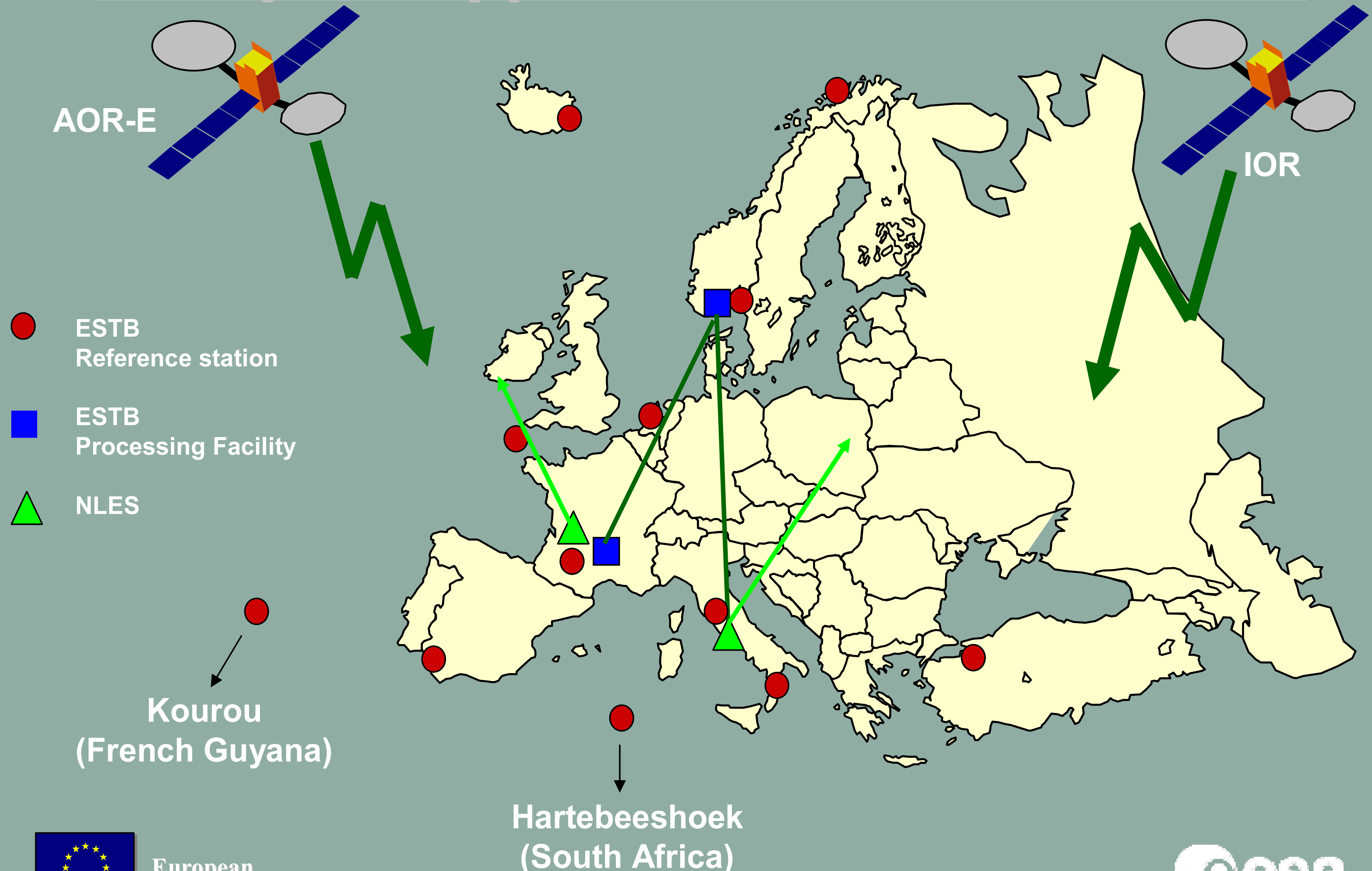
EGNOS Wide Area Network (EWAN)

- **Function**
  - **Links all EGNOS components**
- **Link types:**
  - **MCC-MCC**
    - **High capacity**
    - **EWAN's backbone**
  - **MCC-NLES**
    - **Ensures link with GEO's**
  - **MCC-RIMS**
    - **Frame Relay or VSAT**



EGNOS System Test Bed (ESTB)

Ready for Application Demonstrations



European Commission

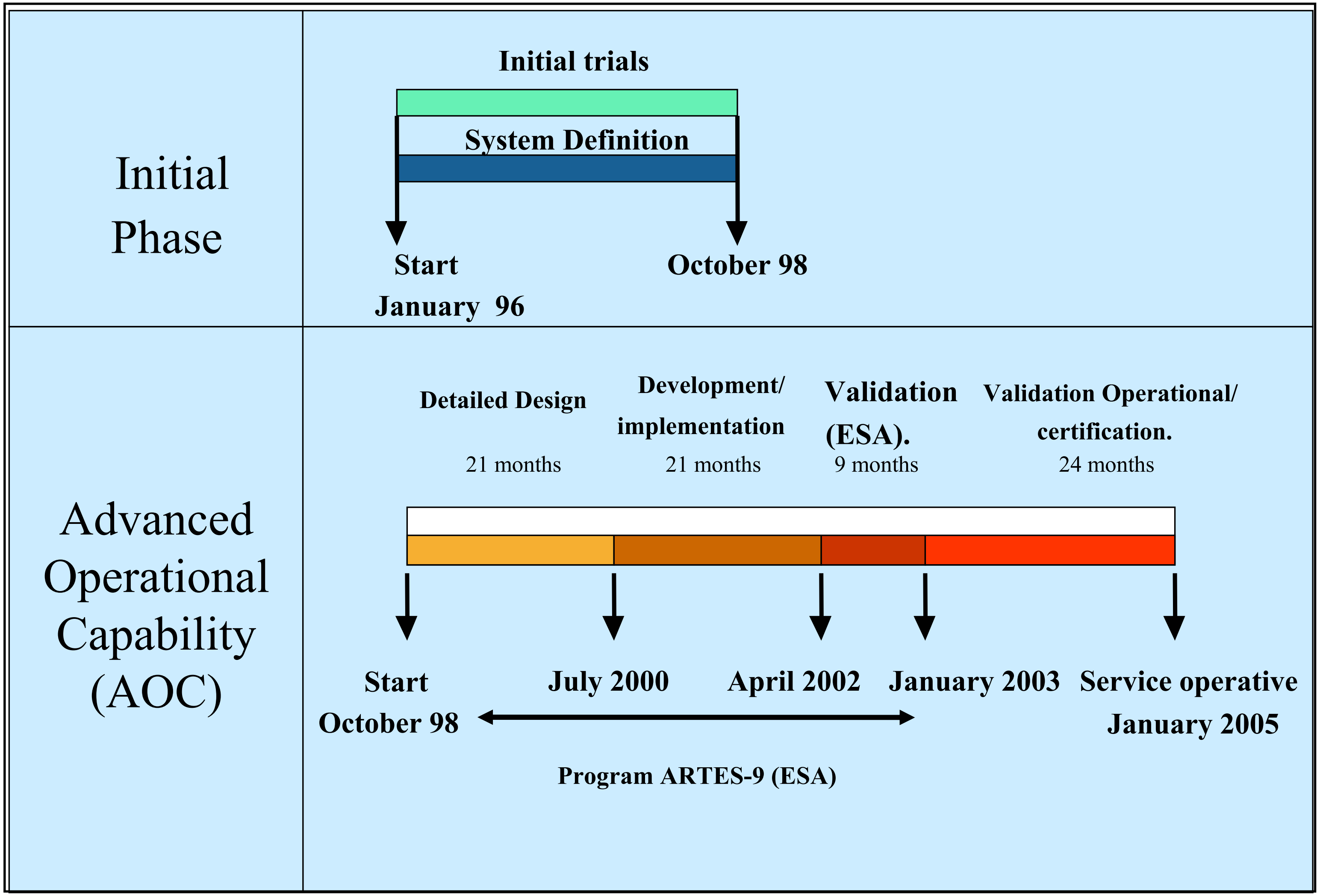
esa

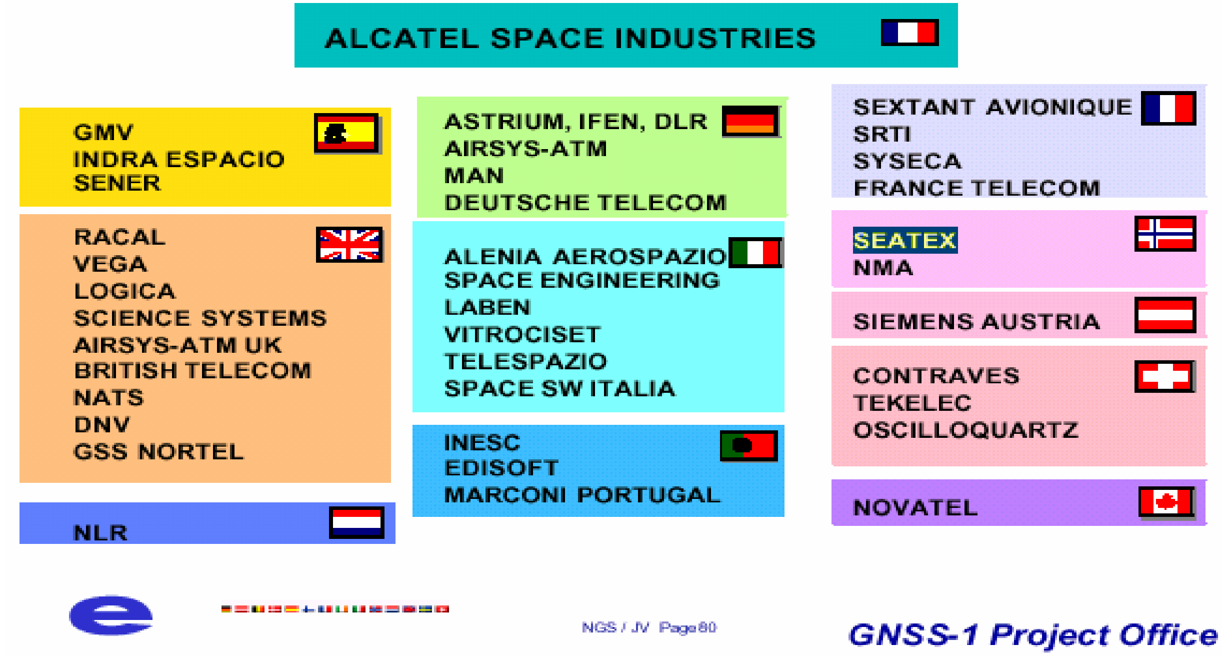
The EGNOS System Test Bed (ESTB)

- Under ESA Contract, European industry has set-up an EGNOS test bed (fully operational since Feb. 2000) . The ESTB is a full-scale real-time prototype of the final EGNOS system.

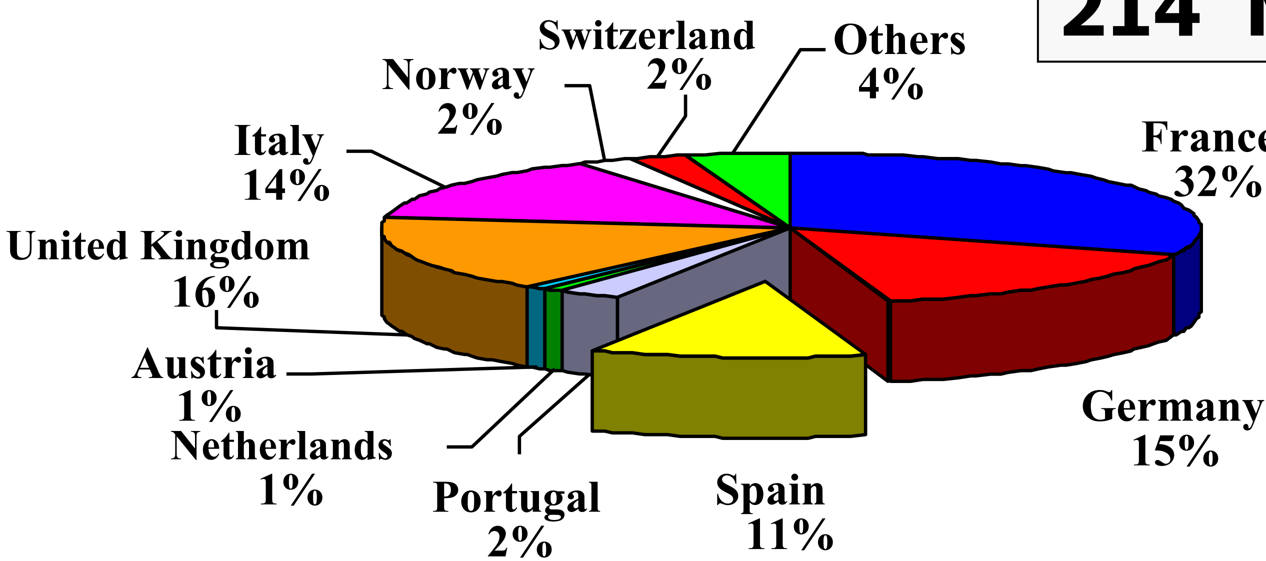
- ESTB main objectives are:
  - to have an assessment of the global performance achievable with EGNOS
  - to analyze in depth specific critical design issues or trade-off's between several options
  - to develop and validate system test methods
  - to demonstrate to the final users the system operation,
  - to provide a representative tool for Civil Aviations to build up SBAS practical experience

EGNOS Operational Milestones




ALCATEL SPACE INDUSTRIES
GMV
INDRA ESPACIO
SENER
RACAL
VEGA
LOGICA
SCIENCE SYSTEMS
AIRSYS-ATM UK
BRITISH TELECOM
NATS
DNV
GSS NORTEL
NLR
ASTRIUM, IFEN, DLR
AIRSYS-ATM
MAN
DEUTSCHE TELECOM
ALENIA AEROSPAZIO
SPACE ENGINEERING
LABEN
VITROCISET
TELESPAZIO
SPACE SW ITALIA
INESC
EDISOFT
MARCONI PORTUGAL
SEXTANT AVIONIQUE
SRTI
SYSECA
FRANCE TELECOM
SEATEX
NMA
SIEMENS AUSTRIA
CONTRAVES
TEKELEC
OSCILLOQUARTZ
NOVATEL
NGS / JV Page 80
GNSS-1 Project Office

214 M EUR


Switzerland 2%
Others 4%
Norway 2%
Italy 14%
France 32%
United Kingdom 16%
Austria 1%
Netherlands 1%
Portugal 2%
Spain 11%
Germany 15%

EGNOS Benefits

- Aviation, maritime navigation, Railways.
- Road community: car navigation, fleet management, road pricing, autonomous vehicle guidance, etc.
- Timing and telecommunications: synchronization of internet nodes; synchronization of mobile base stations, etc.
- Agriculture: precision farming, GIS applications, automation of mobile agriculture, etc).
- Many others: fishery, search and rescue, land surveying, meteorology, land survey, leisure, etc.

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PART II

Data Processing

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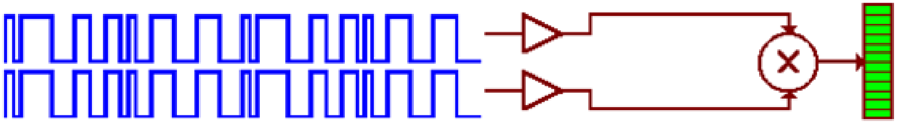
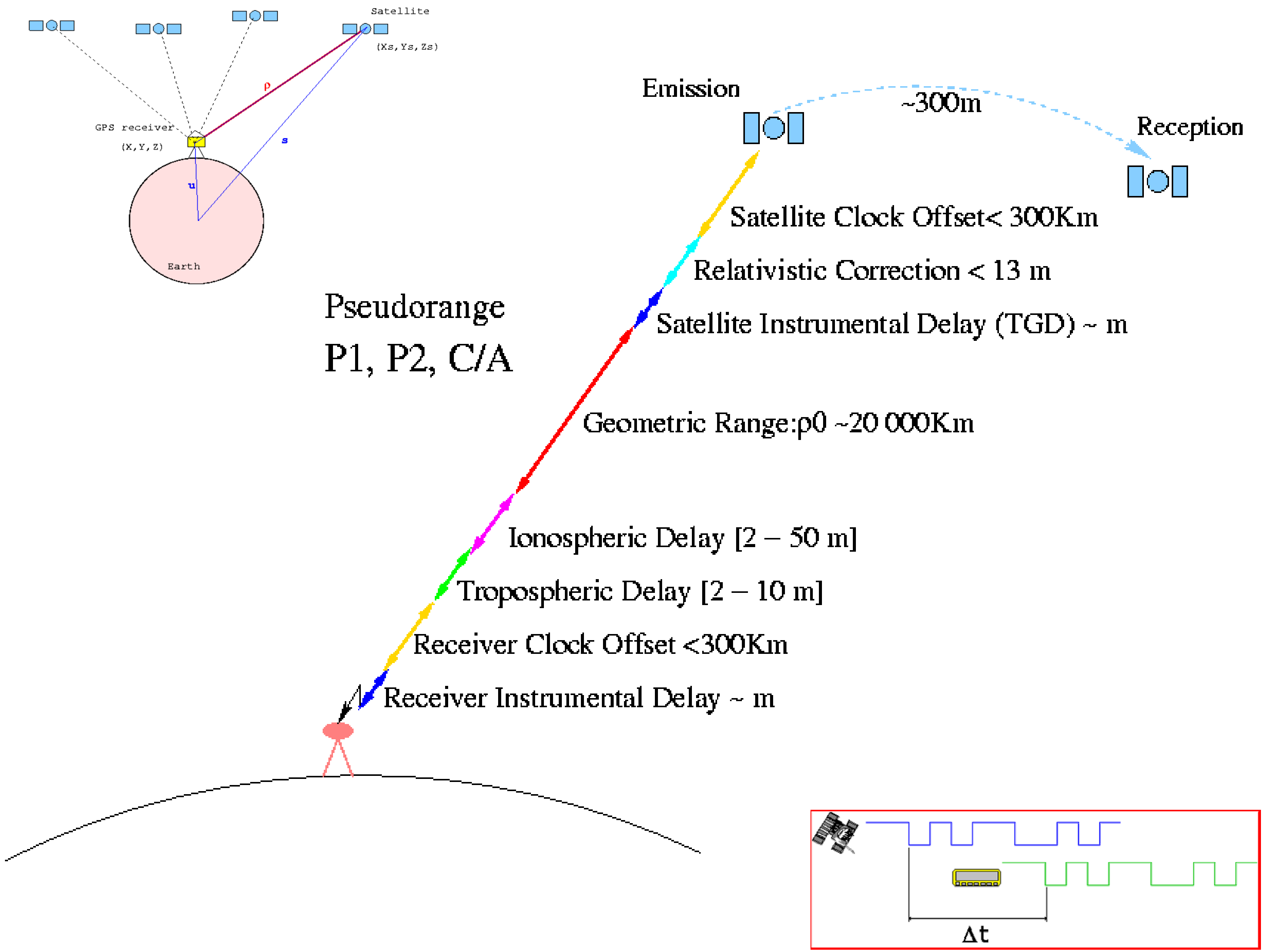
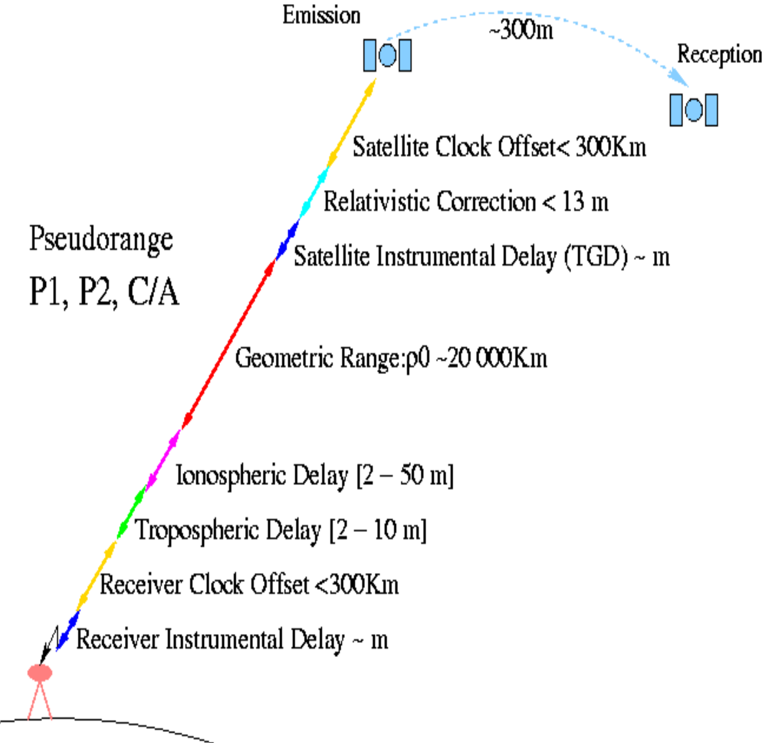
DATA PROCESSING

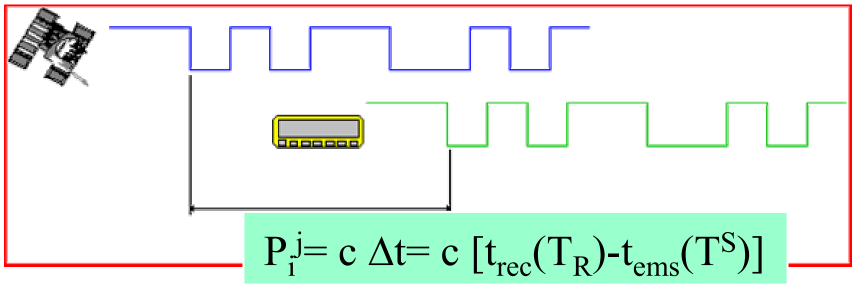
Navigation equations
and
SBAS Differential Corrections and Integrity




Satellite
(Xs,Ys,Zs)
ρ
s
GPS receiver
(X,Y,Z)
u
Earth
Pseudorange
P1, P2, C/A
Emission
~300m
Reception
Satellite Clock Offset< 300Km
Relativistic Correction < 13 m
Satellite Instrumental Delay (TGD) ~ m
Geometric Range:ρ0 ~20 000Km
Ionospheric Delay [2 – 50 m]
Tropospheric Delay [2 – 10 m]
Receiver Clock Offset <300Km
Receiver Instrumental Delay ~ m
Δt

PSEUDORANGE MODELING



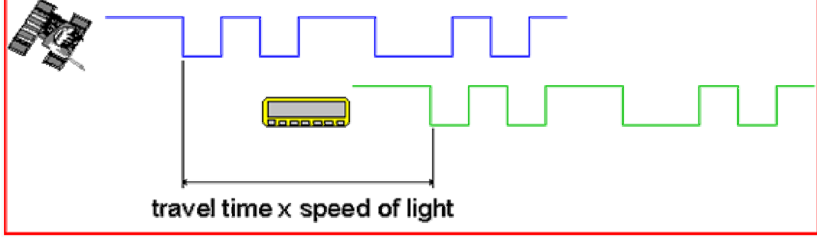


$$P_i^j = \rho_i^j + c \cdot (dt_i - dt^j) + \sum \delta$$

where:

$$\sum \delta = rel_i^j + Trop_i^j + Ion_i^j + K_i + TGD^j + \varepsilon^j$$

- Pseudorange modeling



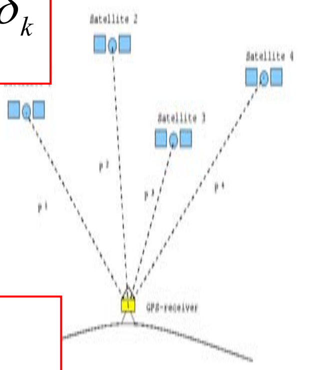
$$P_i^j = \rho_i^j + c\cdot(dt_i - dt^j) + \sum \delta_k$$

Taylor linearization of ρ:

$$\rho_i^j = \sqrt{(x_i - x^j)^2 + (y_i - y^j)^2 + (z_i - z^j)^2} \approx \rho_{i0}^j + \frac{x_{i_0} - x^j}{\rho_{i_0}^j}\Delta x_i + \frac{y_{i_0} - y^j}{\rho_{i_0}^j}\Delta y_i + \frac{z_{i_0} - z^j}{\rho_{i_0}^j}\Delta z_i$$

$$P_i^j \approx \rho_{i_0}^j + \frac{x_{i_0} - x^j}{\rho_{i_0}^j}\Delta x_i + \frac{y_{i_0} - y^j}{\rho_{i_0}^j}\Delta y_i + \frac{z_{i_0} - z^j}{\rho_{i_0}^j}\Delta z_i + c(dt_i - dt^j) + \sum \delta_k$$

$$x_i = x_{io} + \Delta x_i \quad ; \quad y_i = y_{io} + \Delta y_i \quad ; \quad z_i = z_{io} + \Delta z_i$$



- Navigation Equations System:

$$\begin{bmatrix} P_i^1 - \rho_{i_o}^1 + dt^1 - \sum \delta_k^{\ 1} \\ P_i^2 - \rho_{i_o}^2 + dt^2 - \sum \delta_k^{\ 2} \\ \cdots\cdots \\ P_i^n - \rho_{i_o}^n + dt^n - \sum \delta_k^{\ n} \end{bmatrix} = \begin{bmatrix} \frac{x_{i_0} - x^1}{\rho_{i_o}^1} & \frac{y_{i_0} - y^1}{\rho_{i_o}^1} & \frac{z_{i_0} - z^1}{\rho_{i_o}^1} & 1 \\ \frac{x_{i_0} - x^2}{\rho_{i_o}^2} & \frac{y_{i_0} - y^2}{\rho_{i_o}^2} & \frac{z_{i_0} - z^2}{\rho_{i_o}^2} & 1 \\ & \cdots\cdots\cdots & & \\ \frac{x_{i_0} - x^n}{\rho_{i_o}^n} & \frac{y_{i_0} - y^n}{\rho_{i_o}^n} & \frac{z_{i_0} - z^n}{\rho_{i_o}^n} & 1 \end{bmatrix} \begin{bmatrix} \Delta x_i \\ \Delta y_i \\ \Delta z_i \\ cdt_i \end{bmatrix}$$

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• Navigation Solution:

$$Y = G \cdot X$$

$$\hat{X} = \left(G^T W G\right)^{-1} G^T W Y$$

where

$$X = \begin{bmatrix} \Delta x_i \\ \Delta y_i \\ \Delta z_i \\ cdt_i \end{bmatrix}$$

•NOTE

$$G^j = \left[\frac{x_{i_0} - x^j}{\rho_{i_o}^j}, \frac{y_{i_0} - y^j}{\rho_{i_o}^j}, \frac{z_{i_0} - z^j}{\rho_{i_o}^j}, 1 \right] \Longrightarrow X = \begin{bmatrix} \Delta x_i \\ \Delta y_i \\ \Delta z_i \\ cdt_i \end{bmatrix}$$

$$G^j = \left[\cos El_i^j \cos Az_i^j, \cos El_i^j \sin Az_i^j, \sin El_i^j, 1 \right] \Longrightarrow X = \begin{bmatrix} \Delta N_i \\ \Delta E_i \\ \Delta U_i \\ cdt_i \end{bmatrix}$$

PROTECTION LEVELS:

$$Y = G \cdot X$$

$$\hat{X} = \left(G^T W G\right)^{-1} G^T W Y$$

$$X = \left[\Delta N, \Delta E, \Delta U, cdt\right]$$

$$\mathbf{P_x} = \mathbf{S}\,\mathbf{P_y}\,\mathbf{S^T} = \begin{bmatrix} d_N^2 & d_{NE} & d_{NV} & d_{NT} \\ d_{NE} & d_E^2 & d_{EV} & d_{ET} \\ d_{NV} & d_{EV} & d_V^2 & d_{VT} \\ d_{NT} & d_{ET} & d_{VT} & d_T^2 \end{bmatrix}$$

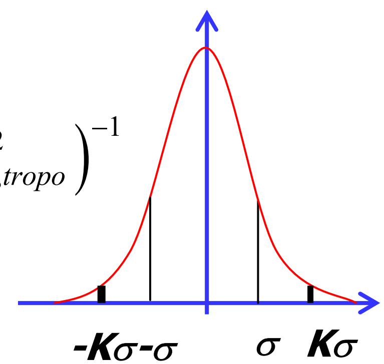
$$HPL = 6.00\sqrt{\frac{d_N^2 + d_E^2}{2} + \sqrt{\left(\frac{d_N^2 - d_E^2}{2}\right)^2 + d_{NE}^2}}$$

$$\mathbf{S} = \left(\mathbf{G^T W G}\right)^{-1} \mathbf{G^T W}$$

$$VPL = 5.33\, d_V$$

$$\mathbf{W} = \begin{bmatrix} w_1 & & 0 \\ & \ddots & \\ 0 & & w_N \end{bmatrix}$$

$$w_i = \left(\sigma_{i,UDRE}^2 + \sigma_{i,UIRE|\varepsilon=0}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2\right)^{-1}$$



$$\mathbf{P_y} = \begin{bmatrix} \sigma_1^2 & & 0 \\ & \ddots & \\ 0 & & \sigma_N^2 \end{bmatrix}$$

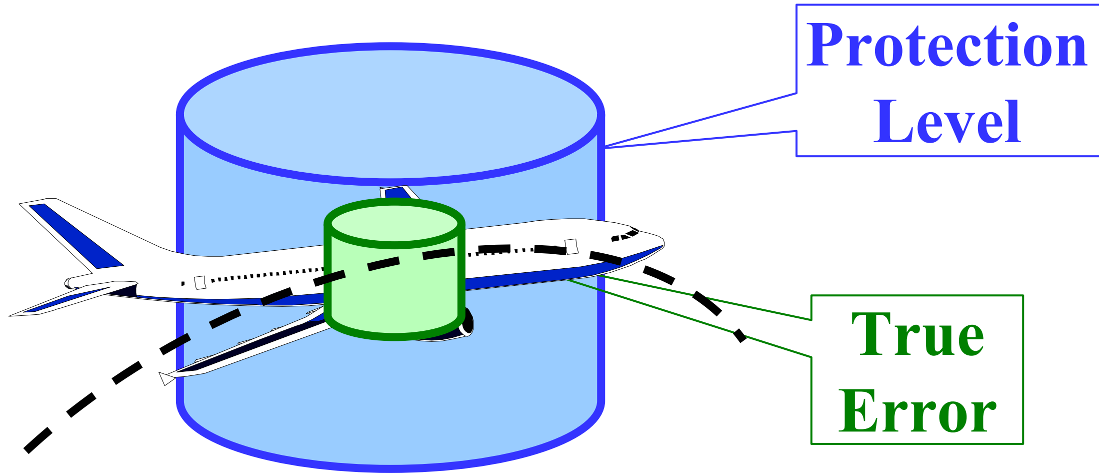
$$\sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i\,UIRE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2$$

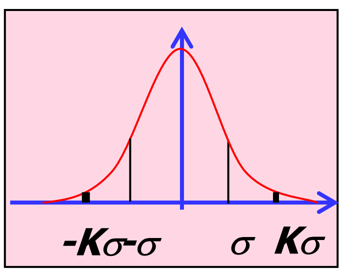
$$X \sim N(0,1)$$

$$P(|X| > 5.33) = 10^{-7}$$

Users know the receiver-satellites geometry and can compute bounds on the horizontal and vertical position errors.

These bounds are called Protection Levels (HPL and VPL). They provide good confidence (10^{-7}/hour probability) that the true position is within a bubble around the computed position.





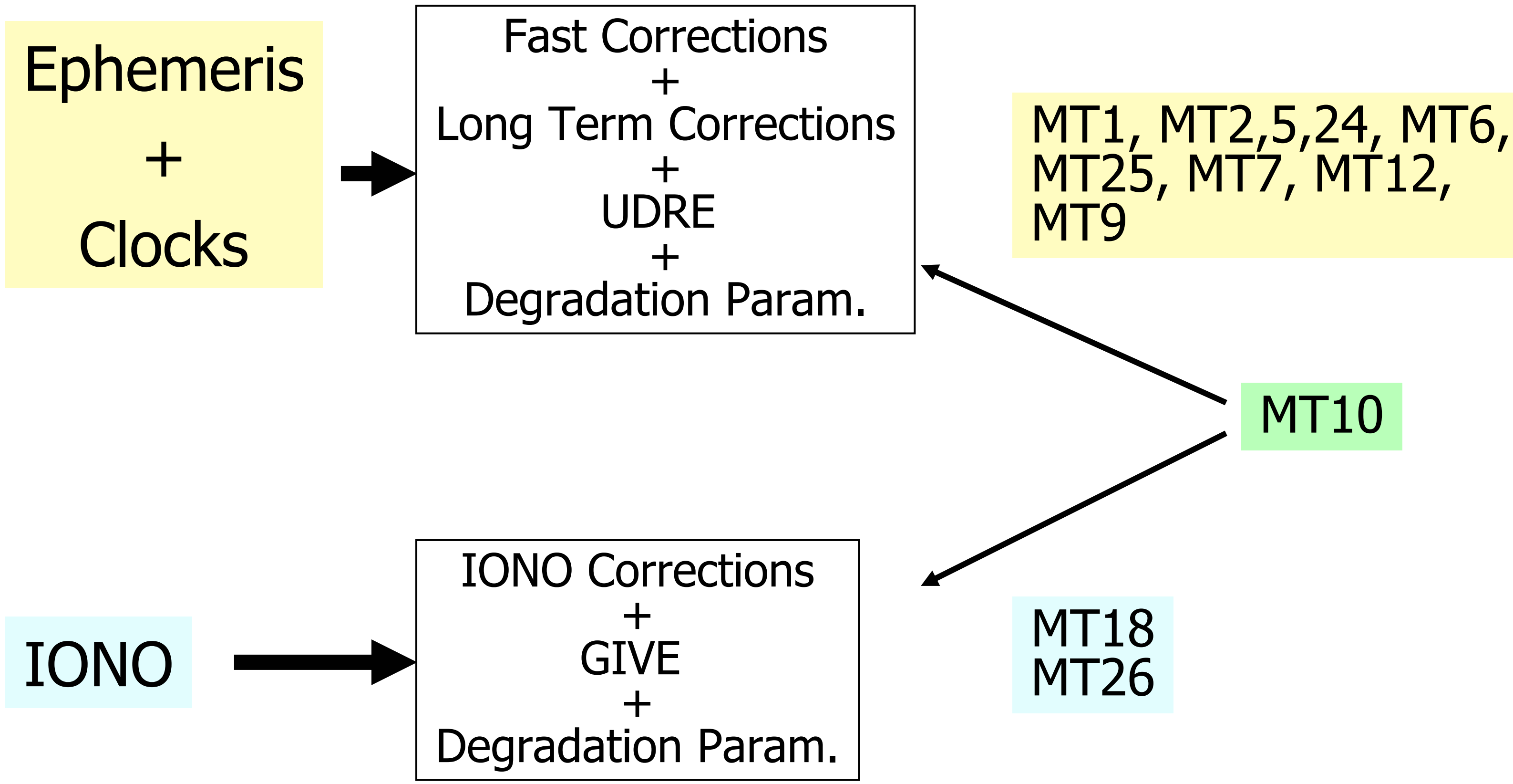
Tail area Probability

P(VPE>VPL) < 10^{-7} /sample

$$VPL = K_V \sqrt{\sum_{i=1}^{N} s_{V_i}^2 \sigma_i^2}$$

$$\sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i,UIRE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2$$

GEOMETRY



$$Y = C1 + PRC - \rho^{*} + \Delta t^{sat} + dt^{sat} + rel - TGD + IONO + TROP$$

$$\sigma^2 = \sigma_{flt}^2 + \sigma_{UIRE}^2 + \sigma_{air}^2 + \sigma_{tropo}^2$$

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Fast and Long-Term Correction Degradation

$$\sigma^2_{i,flt} = \begin{cases} \left(\sigma_{UDRE} + \varepsilon_{fc} + \varepsilon_{rrc} + \varepsilon_{ltc} + \varepsilon_{er}\right)^2 & , if \quad RSS_{UDRE} = 0 \quad (MT10) \\ \sigma^2_{UDRE} + \varepsilon^2_{fc} + \varepsilon^2_{rrc} + \varepsilon^2_{ltc} + \varepsilon^2_{er} & , if \quad RSS_{UDRE} = 1 \quad (MT10) \end{cases}$$

$$\varepsilon_{fc} = a \frac{(t - t_u + t_{lat})^2}{2}$$

$$\varepsilon_{ltc,v0} = C_{ltc,v0}\, floor\left(\frac{t - t_{ltc}}{I_{ltc,v0}}\right)$$

$(when \ IODF \neq 3)$

$$\varepsilon_{ltc,v1} = \begin{cases} 0 & , if \quad t_0 < t < t_0 + I_{ltc\_v1} \\ C_{lts\_lsb} + C_{ltc\_v1} \max\{0, t_0 - t, t - t_0 - I_{ltc\_v1}\} & , otherwise \end{cases}$$

$$\varepsilon_{er} = \begin{cases} 0 & \text{Neither fast nor long term corrections have time out for precision approach} \\ C_{er} & \text{Otherwise} \end{cases}$$

$IODF_{current}, IODF_{previous} \neq 3$

$$\varepsilon_{rrc} = \begin{cases} 0 & , (IODF_{current} - IODF_{previous})_{\mathrm{mod}\,2} = 1 \\ \left(\frac{a\, I_{fc}}{4} + \frac{B_{rrc}}{\Delta t}\right)(t - t_{of}) & , (IODF_{current} - IODF_{previous})_{\mathrm{mod}\,2} \neq 1 \end{cases}$$

MT2-6,24

$IODF, UDRE_i$

$t_u = t_{of}$

MT25

$t_{ltc}, v_0 \ or \ v_1$

MT7

$a_i \quad I_{fc,i} \quad t_{lat}$

MT10

$B_{rrc}, C_{ltc\_lsb}, C_{ltc\_v1},$
$I_{ltc\_v1}, C_{ltc\_v0}, I_{ltc\_v0},$
$C_{er}, RSS_{UDRE},$
$C_{iono\_ramp}, C_{iono\_step},$
I_{iono}, RSS_{iono}

Degradation of Ionospheric Corrections

$$\sigma^2_{UIRE} = F^2_{pp}\sigma^2_{UIVE}$$

$$F_{pp} = \left[1 - \left(\frac{R_e \cos E}{R_e + h_I}\right)^2\right]^{-\frac{1}{2}}$$

$$\sigma^2_{UIVE} = \sum_{n=1}^{N} W_n\left(x_{pp}, y_{pp}\right)\sigma^2_{n,ionogrid}\,, \qquad N = 4\, or\, 3$$

$$\sigma^2_{ionogrid} = \begin{cases} \left(\sigma_{GIVE} + \varepsilon_{iono}\right)^2, if \quad RSS_{iono} = 0 \quad (MT10) \\ \sigma^2_{GIVE} + \varepsilon^2_{iono} \quad , if \quad RSS_{iono} = 1 \quad (MT10) \end{cases}$$

$$\varepsilon_{iono} = C_{iono\_step}\, floor\left(\frac{t - t_{iono}}{I_{iono}}\right) + C_{iono\_ramp}\left(t - t_{iono}\right)$$

MT10

$B_{rrc}, C_{ltc\_lsb}, C_{ltc\_v1},$
$I_{ltc\_v1}, C_{ltc\_v0}, I_{ltc\_v0},$
$C_{er}, RSS_{UDRE},$
$C_{iono\_ramp}, C_{iono\_step},$
I_{iono}, RSS_{iono}

MT26

$t_{iono}, GIVE_i$

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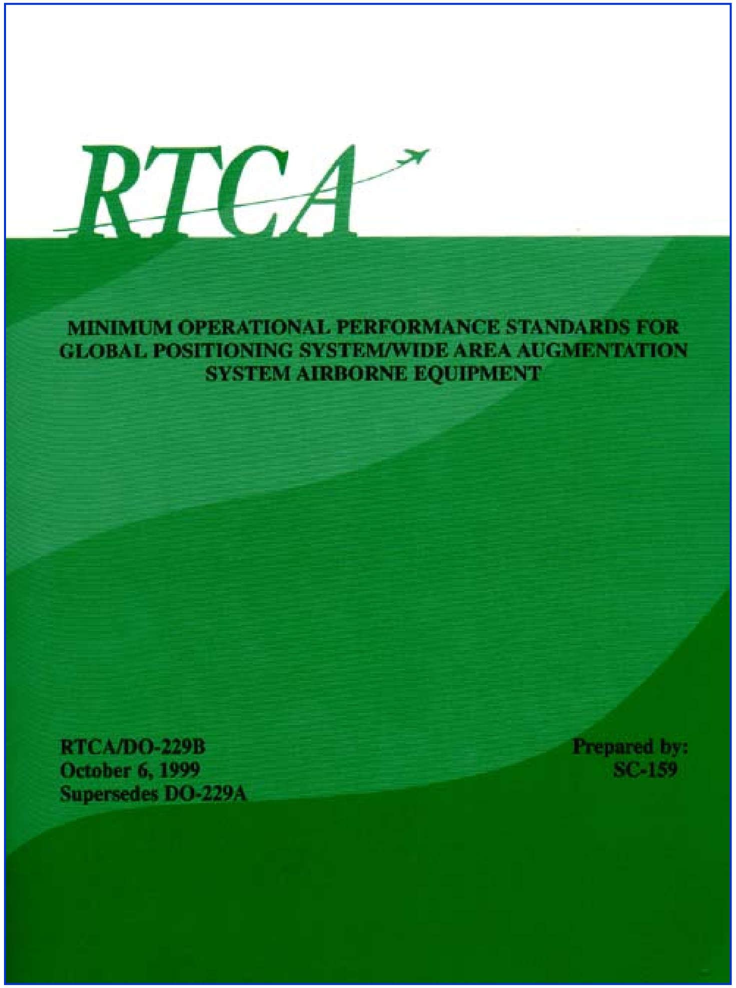
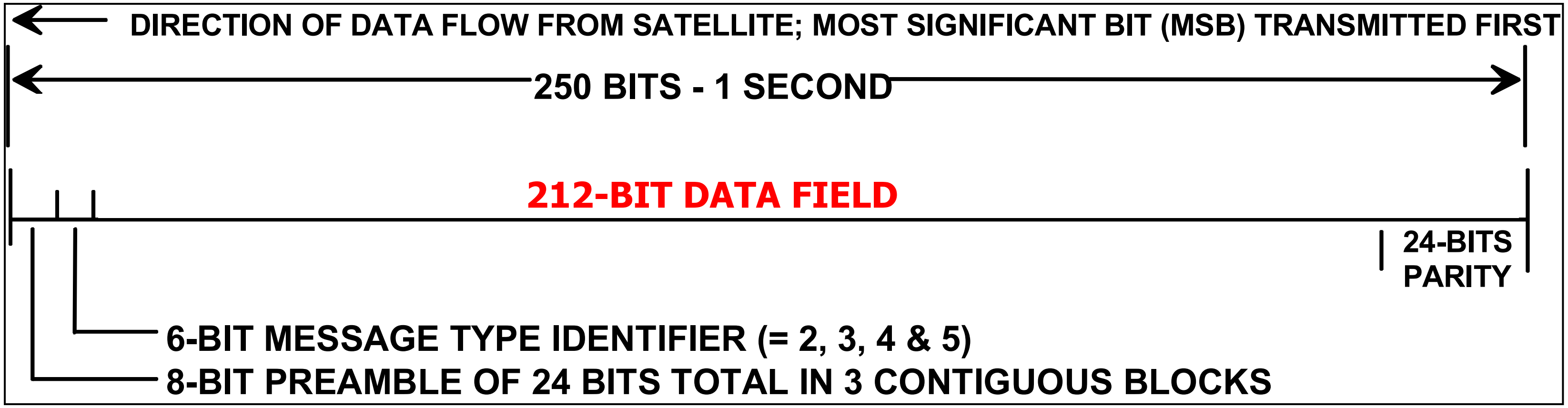
SBAS Differential Corrections and Integrity:

The RTCA/MOPS



Message Format



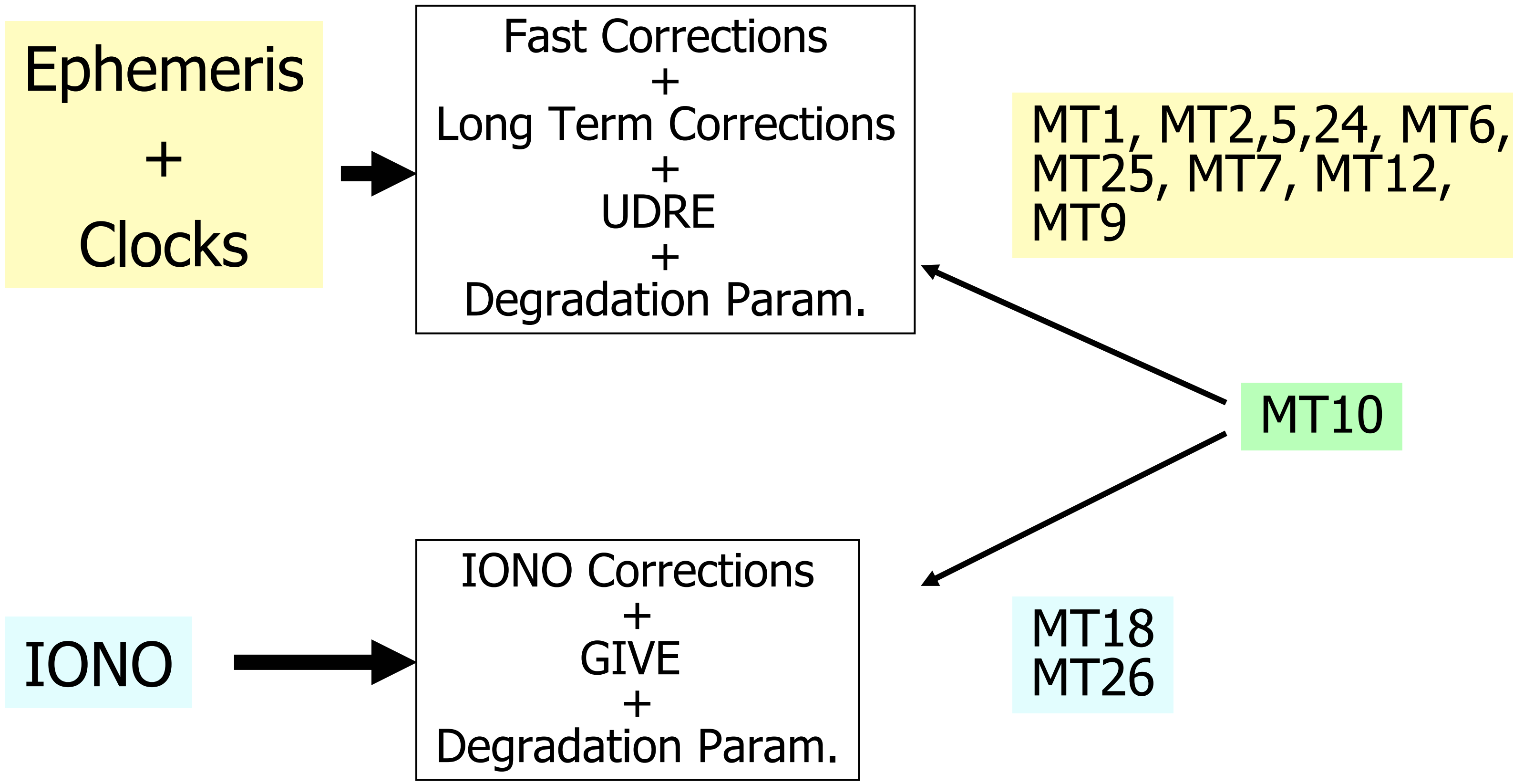
The corrections, even for individual satellites are distributed across several individual messages.

- 250 bits
- One Message per second
- All messages have identical format

EGNOS Broadcast Messages (ICAO SARPS)

MSG 0	Don't use this SBAS signal for anything (for SBAS testing)
MSG 1	PRN Mask assignments, set up to 51 of 210 bits
MSG 2 to 5	Fast corrections
MSG 6	Integrity information
MSG 7	Fast correction degradation factor
MSG 8	*Reserved for future messages*
MSG 9	GEO navigation message (*X*, *Y*, *Z*, time, etc.)
MSG 10	Degradation Parameters
MSG 11	*Reserved for future messages*
MSG 12	SBAS Network Time/UTC offset parameters
MSG 13 to 16	*Reserved for future messages*
MSG 17	GEO satellite almanacs
MSG 18	Ionospheric grid point masks
MSG 19 to 23	*Reserved for future messages*
MSG 24	Mixed fast corrections/long term satellite error corrections
MSG 25	Long term satellite error corrections
MSG 26	Ionospheric delay corrections
MSG 27	SBAS outside service volume degradation
MSG 28 to 61	*Reserved for future messages*
MSG 62	Internal Test Message
MSG 63	Null Message

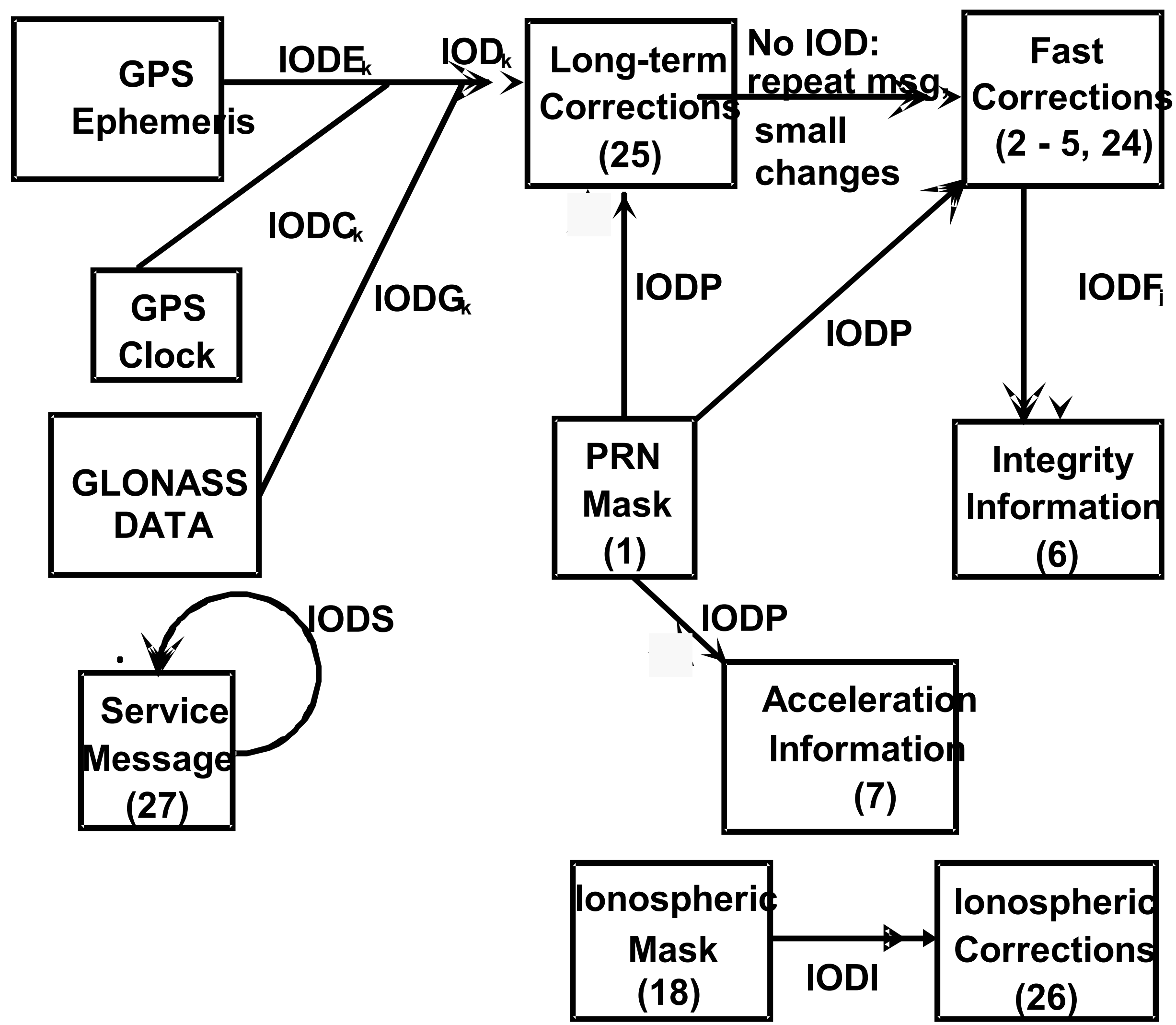
Many Message Types Coordinated Through Issues Data (IOD)



$$Y = C1 + PRC - \rho^{*} + \Delta t^{sat} + dt^{sat} + rel - TGD + IONO + TROP$$

$$\sigma^2 = \sigma_{flt}^2 + \sigma_{UIRE}^2 + \sigma_{air}^2 + \sigma_{tropo}^2$$

Issues of Data (IOD)

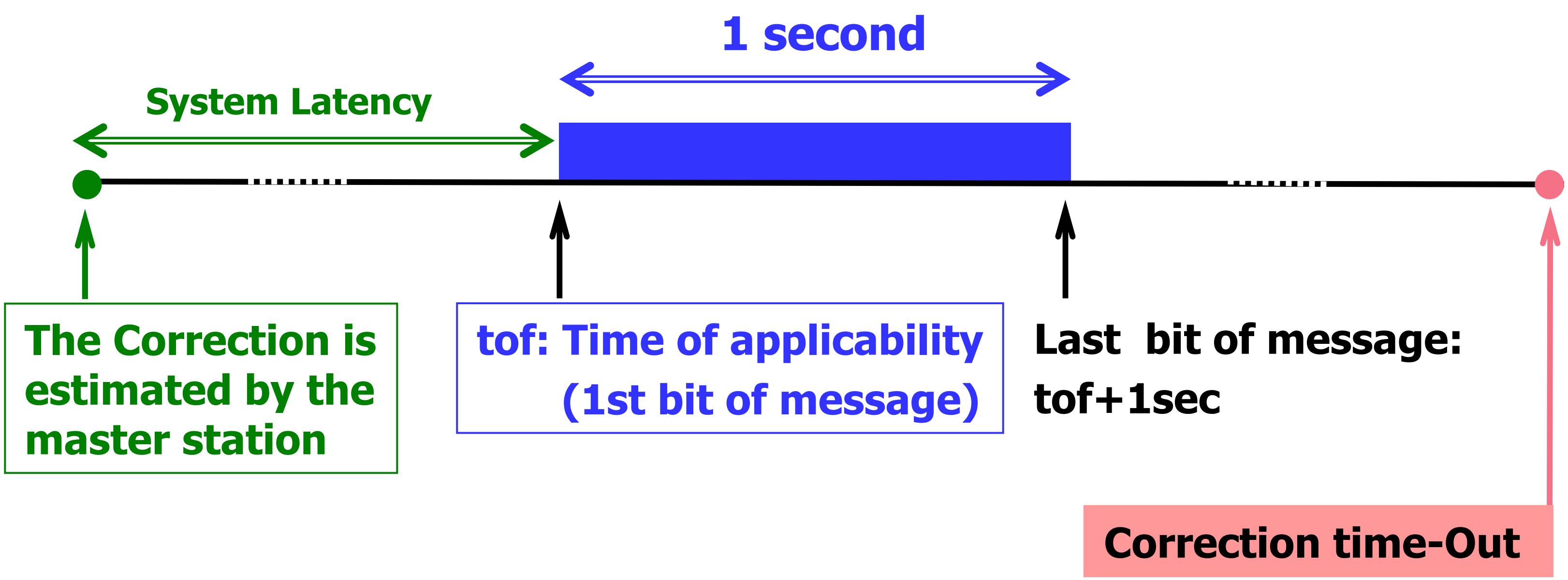


Manuel Hernández-Pajares, J. Miguel Juan, Jaume Sanz, Xavier Prats, February 2002.

Message Time-Outs:

Users can operate even when missing Messages

- Prevents Use of Very Old Data
- Confidence Degrades When Data is Lost
- IODF: Detect Missing Fast Corrections



Data	Associated Message Types	Maximum Update Interval (seconds)	En Route, Terminal, NPA Timeout (seconds)	Precision Approach Timeout (seconds)
WAAS in Test Mode	0	6	N/A	N/A
PRN Mask	1	60	None	None
UDREI	2-6, 24	6	18	12
Fast Corrections	2-5, 24	60	(*)	(*)
Long Term Corrections	24, 25	120	360	240
GEO Nav. Data	9	120	360	240
Fast Correction Degradation	7	120	360	240
Weighting Factors	8	120	240	240
Degradation Parameters	10	120	360	240
Ionospheric Grid Mask	18	300	None	None
Ionospheric Corrections	26	300	600	600
UTC Timing Data	12	300	None	None
Almanac Data	17	300	None	None

(*) Fast Correction Time-Out intervals are given in MT7 [between 12 to 120 sec]

PRN MASK (MT01)

Bit No	1	2	3	4	5	6	.	38	.	120	.	210
Value	0	1	0	1	1	0		1		1		0
PRN		GPS PRN 2		GPS PRN 4	GPS PRN 5			GLONASS Slot 1		AORE PRN 120		
PRN mask Number		1		2	3			21		29		

Each MT01 contains its associated IODP

Up to 51 satellites in 210 slots.

Note: Each Correction set in MT 2-5,5,6,7,24,25 its characterized by its PRN-Mask number, between 1 to 51.

PRN Slot	Assignment
1-37	GPS/GPS Reserved
38-61	GLONASS
62-119	Future GNSS
120-138	GEO/SBAS
139-210	Future GNSS/GEO/SBAS/Pseudolites

Fast Corrections (MT2-5,24)

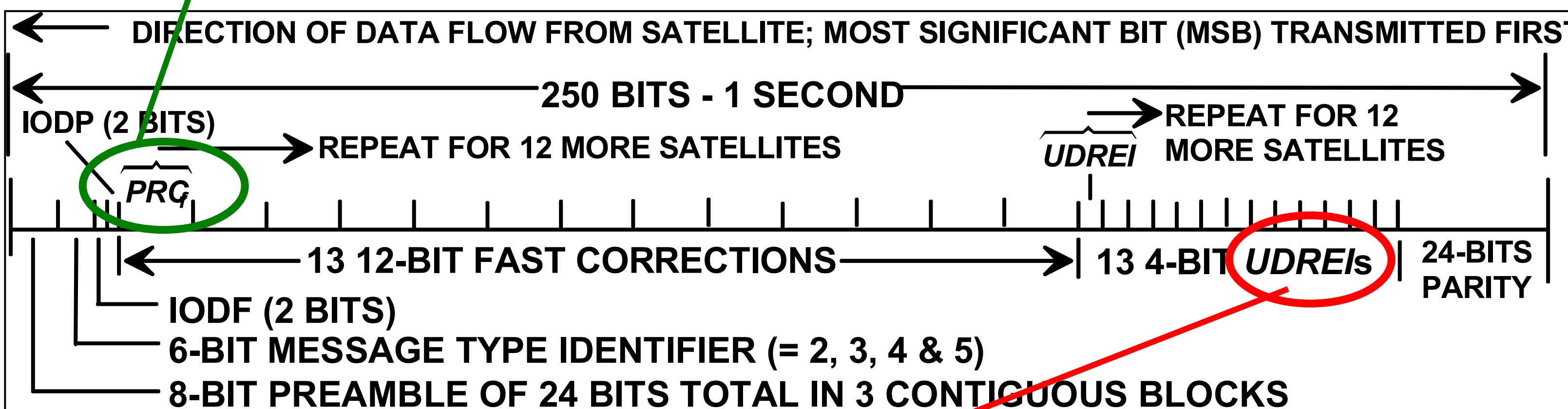
- Primarily Removes SA
  - Common to ALL users
  - Up to 13 Satellites Per Message
  - Pseudorange Correction /confidence Bound
  - Range Rate Formed by Differencing
  - UDRE degrades Over Time
    - Acceleration Term in MT 7
    - Reset when new Message Received

Fast Corrections (MT2-5)

$$PRC(t) = PRC_n + RRC_n(t - t_n)$$

$$RRC_n = \frac{PRC_n - PRC_o}{t_n - t_o}$$

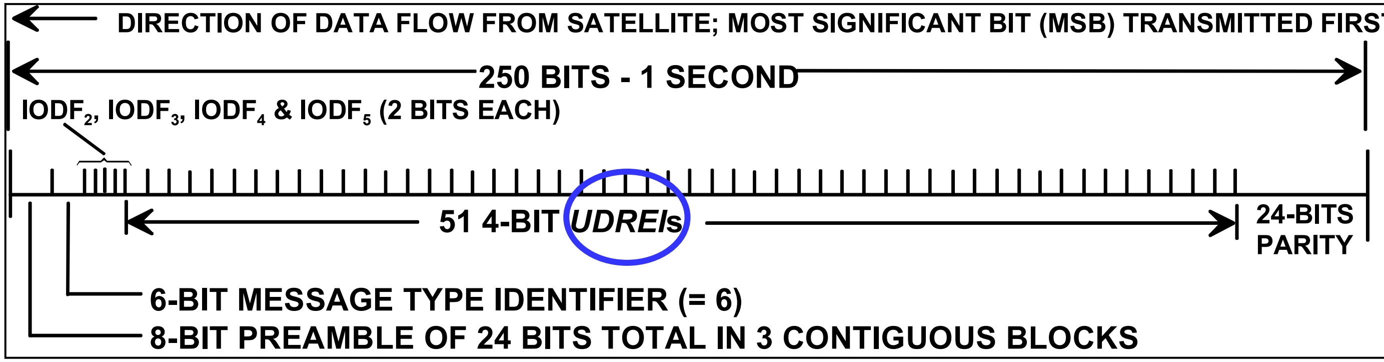
$$Y = C1 + PRC - \rho^* + \Delta t^{sat} + dt^{sat} + rel - TGD + IONO + TROP$$



$(RSS_{UDRE} = 0 \quad [MT10])$

$$\sigma^2_{i,flt} = \sigma^2_{UDRE} + \varepsilon^2_{fc} + \varepsilon^2_{rrc} + \varepsilon^2_{ltc} + \varepsilon^2_{er}$$

Message Type 6



Alarm conditions are indicated with **IODF=3**

- Serves Two Purposes
  - Alarm for Multiple Satellites
    - Includes UDREs for all 51 Satellites
  - Update UDRE in Between Fast Corrections
    - More efficient Use of Bandwidth
    - The receipt of MT6 with matching IODF<3 is equivalent to another reception of last fast correction.

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Evaluation of UDREI

$UDREI_i$	$UDRE_i$ Meters	$\sigma^2_{i,UDRE}$ Meters^2
0	0.75	0.0520
1	1.0	0.0924
2	1.25	0.1444
3	1.75	0.2830
4	2.25	0.4678
5	3.0	0.8315
6	3.75	1.2992
7	4.5	1.8709
8	5.25	2.5465
9	6.0	3.3260
10	7.5	5.1968
11	15.0	20.7870
12	50.0	230.9661
13	150.0	2078.695
14	Not Monitored	Not Monitored
15	Do Not Use	Do Not Use

Comment:

- With SA=off, the FC can be sent less frequently than 6sec, but it is still necessary to update the "integrity status (UDREs)" at the high rate.
- Prec. App: UDRE time-out =12sec

  FC time-out between 12 -120 sec.

The MOPS (RTCA Do 229A) 2.1.1.5.2, establish the satellites deselecting for:

-UDRE=14 (not monitored)

and

-UDRE=15 (don't use)

2.1.4.7.1: In addition, for Precision Approach: UDRE<11.

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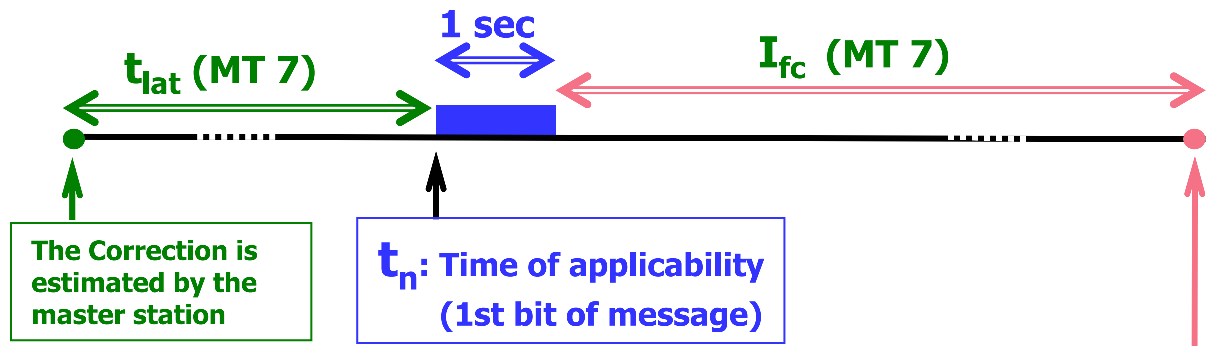
UDRE degradation: The fast correction was estimated by master station at some previous time $t_n - t_{lat}$



$$\sigma^2_{i,flt} = \sigma^2_{UDRE} + \varepsilon^2_{fc} + \varepsilon^2_{rrc} + \varepsilon^2_{ltc} + \varepsilon^2_{er}$$

Acceleration Term (Always included)

$$\varepsilon_{fc} \equiv \frac{a}{2}\left(t - t_{UDRE} + t_{lat}\right)^2$$

Lost Fast Correction Term $(when\ \ IODF \neq 3)$

$$\varepsilon_{rrc} \equiv \left(\frac{a\ I_{fc}}{4} + \frac{B_{rrc}}{t_n - t_o}\right)\left(t - t_n\right)$$

EXAMPLE 1

(From WAAS MOPS: Practical Examples.

Todd Walter)

Time (sec) t	Last Mess. Time (s) tn	Last Mess PRC_n (m)	Last Mess. $IODF_n$	*PRC(t) (m)*	RRC_n	*Error (m)*	σ^2_{flt}	σ^2_{UDRE}	ε^2_{fc}	ε^2_{rrc}
0	-1	0.500	0	-	-		-	-	-	-
3	-1	0.500	0	-	-		-	-	-	-
6	5	-2.125	1	-2.563	-0.4375	0.505	0.0957	0.0924	0.0033	0
9	5	-2.125	1	-3.875	-0.4375	1.045	0.1141	0.0924	0.0217	0
12	11	-3.125	2	-3.292	-0.1667	-0.140	0.0957	0.0924	0.0033	0
15	11	-3.125	2	-3.792	-0.1667	-0.171	0.1141	0.0924	0.0217	0
18	17	-4.000	0	-4.146	-0.1458	0.238	0.0957	0.0924	0.0033	0
21	17	-4.000	0	-4.583	-0.1458	0.373	0.1141	0.0924	0.0217	0
24	17	-4.000	0	-5.021	-0.1458	0.893	0.1699	0.0924	0.0775	0
27	17	-4.000	0	-5.458	-0.1458	1.584	0.2954	0.0924	0.2030	0
30	29	-3.500	2	-3.458	0.0417	0.008	0.0964	0.0924	0.0033	0.00069
33	29	-3.500	2	-3.333	-0.0417	0.479	0.1252	0.0924	0.0217	0.01111
36	35	-2.750	0	-2.625	0.1250	0.537	0.0957	0.0924	0.0033	0
39	35	-2.750	0	-2.250	0.1250	1.100	0.1141	0.0924	0.0217	0

FC update rate 6 sec

Param	Mes. Type	value
$\sigma^2_{UDRE\,(m2)}$	*MT 2*	*0.0924*
a (mm/s2)	*MT 7*	*4.60*
I_{fc} *(sec)*	*MT 7*	*12*

Param	Mes. Type	value
t_{lat} *(sec)*	*MT 7*	*4*
B_{rrc} *(m)*	*MT10*	*0.15*
RSS_{UDRE}	*MT10*	*1*

Time (sec) t	Last Mess. Time (s) tn	Last Mess PRC_n (m)	Last Mess. $IODF_n$	*PRC(t) (m)*	*RRC_n*	*Error (m)*	σ^2_{flt}	σ^2_{UDRE}	ε^2_{fc}	ε^2_{rrc}
0	-1	0.500	0	-	-		-	-	-	-
3	-1	0.500	0	-	-		-	-	-	-
6	5	-2.125	1	-2.563	-0.4375	0.505	0.0957	0.0924	0.0033	0
9	5	-2.125	1	-3.875	-0.4375	1.045	0.1141	0.0924	0.0217	0
12	11	-3.125	2	-3.292	-0.1667	-0.140	0.0957	0.0924	0.0033	0
15	11	-3.125	2	-3.792	-0.1667	-0.171	0.1141	0.0924	0.0217	0
18	17	-4.000	0	-4.146	-0.1458	0.238	0.0957	0.0924	0.0033	0
21	17	-4.000	0	-4.583	-0.1458	0.373	0.1141	0.0924	0.0217	0
24	17	-4.000	0	-5.021	-0.1458	0.893	0.1699	0.0924	0.0775	0
27	17	-4.000	0	-5.458	-0.1458	1.584	0.2954	0.0924	0.2030	0
30	29	-3.500	2	-3.458	0.0417	0.008	0.0964	0.0924	0.0033	0.00069
33	29	-3.500	2	-3.333	-0.0417	0.479	0.1252	0.0924	0.0217	0.01111
36	35	-2.750	0	-2.625	0.1250	0.537	0.0957	0.0924	0.0033	0
39	35	-2.750	0	-2.250	0.1250	1.100	0.1141	0.0924	0.0217	0

$$PRC(t) = PRC_n + RRC_n (t - t_n)$$

$$RRC_n = \frac{PRC_n - PRC_o}{t_n - t_o}$$

$$\sigma^2_{i,flt} = \sigma^2_{UDRE} + \varepsilon^2_{fc} + \varepsilon^2_{rrc} + \varepsilon^2_{ltc} + \varepsilon^2_{er}$$

$$\varepsilon_{fc} \equiv \frac{a}{2}(t - t_n + t_{lat})^2$$

$$\varepsilon_{rrc} \equiv \left(\frac{a\ I_{fc}}{4} + \frac{B_{rrc}}{t_n - t_o}\right)(t - t_n)$$

$\varepsilon_{rrc}=0$ **when no mess. are missed**

RRC Time − Out

$\Delta t = t_n - t_o > I_{fc}$

$t - t_n > 8\Delta t$

Ifc=12sec

PRC Time − Out

$t - t_n > I_{fc} + 1$

UDRE Time-Out

$t-t_n>13$

Manuel Hernández-Pajares, J. Miguel Juan, Jaume Sanz, Xavier Prats, February 2002.

Time (sec) t	Last Mess. Time (s) tn	Last Mess PRC_n (m)	Last Mess. $IODF_n$	*PRC(t) (m)*	*RRC_n*	*Error (m)*	σ^2_{flt}	σ^2_{UDRE}	ε^2_{fc}	ε^2_{rrc}
0	-1	0.500	0	-	-		-	-	-	-
3	-1	0.500	0	-	-		-	-	-	-
6	5	-2.125	1	-2.563	-0.4375	0.505	0.0957	0.0924	0.0033	0
9	5	-2.125	1	-3.875	-0.4375	1.045	0.1141	0.0924	0.0217	0
12	11	-3.125	2	-3.292	-0.1667	-0.140	0.0957	0.0924	0.0033	0
15	11	-3.125	2	-3.792	-0.1667	-0.171	0.1141	0.0924	0.0217	0
18	17	-4.000	0	-4.146	-0.1458	0.238	0.0957	0.0924	0.0033	0
21	17	-4.000	0	-4.583	-0.1458	0.373	0.1141	0.0924	0.0217	0
24	17	-4.000	0	-5.021	-0.1458	0.893	0.1699	0.0924	0.0775	0
27	17	-4.000	0	-5.458	-0.1458	1.584	0.2954	0.0924	0.2030	0
30	29	-3.500	2	-3.458	0.0417	0.008	0.0964	0.0924	0.0033	0.00069
33	29	-3.500	2	-3.333	-0.0417	0.479	0.1252	0.0924	0.0217	0.01111
36	35	-2.750	0	-2.625	0.1250	0.537	0.0957	0.0924	0.0033	0
39	35	-2.750	0	-2.250	0.1250	1.100	0.1141	0.0924	0.0217	0

$$PRC(t) = PRC_n + RRC_n (t - t_n)$$

$$RRC_n = \frac{PRC_n - PRC_o}{t_n - t_o}$$

$$\sigma^2_{i,flt} = \sigma^2_{UDRE} + \varepsilon^2_{fc} + \varepsilon^2_{rrc} + \varepsilon^2_{ltc} + \varepsilon^2_{er}$$

$$\varepsilon_{fc} \equiv \frac{a}{2}\left(t - t_n + t_{lat}\right)^2$$

$$\varepsilon_{rrc} \equiv \left(\frac{a\ I_{fc}}{4} + \frac{B_{rrc}}{t_n - t_o}\right)(t - t_n)$$

$\varepsilon_{rrc}=0$ **when no mess. are missed**

$RRC\ Time-Out$

$\Delta t = t_n - t_o > I_{fc}$

$t - t_n > 8\Delta t$

Ifc=12sec

$PRC\ \ Time-Out$

$t - t_n > I_{fc} + 1$

UDRE Time-Out
$t-t_n>13$

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Time (sec) t	Last Mess. Time (s) tn	Last Mess PRC_n (m)	Last Mess. $IODF_n$	*PRC(t) (m)*	*RRC_n*	*Error (m)*	σ^2_{flt}	σ^2_{UDRE}	ε^2_{fc}	ε^2_{rrc}
0	-1	0.500	0	-	-		-	-	-	-
3	-1	0.500	0	-				-	-	-
6	5	-2.125	1	-2.5			57	0.0924	0.0033	0
9	5	-2.125	1	-3.8			41	0.0924	0.0217	0
12	11	-3.125	2	-3.2			57	0.0924	0.0033	0
15	11	-3.125	2	-3.7			41	0.0924	0.0217	0
18	17	-4.000	0	-4.146	-0.1458	0.238	0.0957	0.0924	0.0033	0
21	17	-4.000	0	-4.583	-0.1458	0.373	0.1141	0.0924	0.0217	0
24	17	-4.000	0	-5.021	-0.1458	0.893	0.1699	0.0924	0.0775	0
27	17	-4.000	0	-5.458	-0.1458	1.584	0.2954	0.0924	0.2030	0
30	29	-3.500	2	-3.458	0.0417	0.008	0.0964	0.0924	0.0033	0.00069
33	29	-3.500	2	-3.333	-0.0417	0.479	0.1252	0.0924	0.0217	0.01111
36	35	-2.750	0	-2.625	0.1250	0.537	0.0957	0.0924	0.0033	0
39	35	-2.750	0	-2.250	0.1250	1.100	0.1141	0.0924	0.0217	0

The IODEs are not in sequence and the user is aware that a FC is missing.
RRC is formed using IODFs out of sequence => ε^2_{rrc}

$$PRC(t) = PRC_n + RRC_n (t - t_n)$$

$$RRC_n = \frac{PRC_n - PRC_o}{t_n - t_o}$$

$$\sigma^2_{i,flt} = \sigma^2_{UDRE} + \varepsilon^2_{fc} + \varepsilon^2_{rrc} + \varepsilon^2_{ltc} + \varepsilon^2_{er}$$

$$\varepsilon_{fc} \equiv \frac{a}{2}\left(t - t_n + t_{lat}\right)^2$$

$$\varepsilon_{rrc} \equiv \left(\frac{a\ I_{fc}}{4} + \frac{B_{rrc}}{t_n - t_o}\right)(t - t_n)$$

$\varepsilon_{rrc}=0$ when no mess. are missed

RRC Time − Out

$\Delta t = t_n - t_o > I_{fc}$

$t - t_n > 8\Delta t$

Ifc=12sec

PRC Time − Out

$t - t_n > I_{fc} + 1$

UDRE Time-Out

$t-t_n>13$

EXAMPLE 2

(From WAAS MOPS: Practical Examples.
Todd Walter)

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$$\sigma^2_{i,flt} = \sigma^2_{UDRE} + \varepsilon^2_{fc} + \varepsilon^2_{rrc} + \varepsilon^2_{ltc} + \varepsilon^2_{er}$$

Time (sec)	Last Mes Time (s)	Last Mess Type	Last Mes IODF	t_{UDRE}	σ^2_{flt}	σ^2_{UDRE}	ε^2_{fc}	ε^2_{rrc}
0	-1	2	0	-1	0.052014	0.0520	0.000014	0
6	5	6	0	5	0.052014	0.0520	0.000014	0
12	11	6	0	11	0.052014	0.0520	0.000014	0
18	17	6	0	17	0.092414	0.0924	0.000014	0
24	23	6	0	23	0.092414	0.0924	0.000014	0
30	29	2	1	29	0.052014	0.0520	0.000014	0
36	35	6	1	35	0.052014	0.0520	0.000014	0
42	41	6	1	41	0.052014	0.0520	0.000014	0
48	47	-	-	41	0.052329	0.0520	0.000329	0
54	53	6	1	53	0.092414	0.0924	0.000014	0
60	59		-	53	0.092729	0.0924	0.000329	0
66	65	6	2	53	0.094297	0.0924	0.001897	0
72	71	6	2	53	0.092696	0.0924	0.006296	0
78	77	6	2	53	0.108310	0.0924	0.015910	0
84	83	6	2	53	0.430000	0.0924	0.337600	0
90	89	2	0	89	0.052074	0.0520	0.000014	0.000060
96	95	6	0	95	0.054732	0.0520	0.000014	0.002720
102	101	6	0	101	0.061394	0.0520	0.000014	0.009380
108	107	6	0	107	0.122814	0.0924	0.000014	0.030400
114	113	6	0	113	0.027104	0.0924	0.000014	0.034690
120	119	2	1	119	0.052014	0.0520	0.000014	0
126	125	6	1	125	0.052014	0.0520	0.000014	0
132	131	6	1	131	0.052014	0.0520	0.000014	0
138	137	6	3	119	0.092696	0.0924	0.006296	0
144	143	6	3	119	0.108310	0.0924	0.015910	0
150	149	2	2	149	0.052014	0.0520	0.000014	0

$$\varepsilon_{fc} \equiv \frac{a}{2}\left(t - t_{UDRE} + t_{lat}\right)^2$$

$$\varepsilon_{rrc} \equiv \left(\frac{a\ I_{fc}}{4} + \frac{B_{rrc}}{t_n - t_o}\right)(t - t_n)$$

ε_{rrc}=0 when no messages are missed

Param	Mes. Type	value
σ^2_{UDRE} (m2)	*MT 2,6*	*0.0520* *0.0924*
a (mm/s2)	*MT 7*	*0.30*
I_{fc} (sec)	*MT 7*	*66*
t_l (sec)	*MT 7*	*4*
B_{rrc} (m)	*MT10*	*0.15*
RSS_{UDRE}	*MT10*	*1*

MT 2 update rate 30 sec
MT 6 update rate 6 sec

$$\sigma^2_{i,flt} = \sigma^2_{UDRE} + \varepsilon^2_{fc} + \varepsilon^2_{rrc} + \varepsilon^2_{ltc} + \varepsilon^2_{er}$$

Time t (s)	Last Mes t2, t6 (s)	Last Mess Type	Last Mes IODF	t_{UDRE}	σ^2_{flt}	σ^2_{UDRE}	ε^2_{fc}	ε^2_{rrc}
0	-1	2	0	-1	0.052014	0.0520	0.000014	0
6	5	6	0	5	0.052014	0.0520	0.000014	0
12	11	6	0	11	0.052014	0.0520	0.000014	0
18	17	6	0	17	0.092414	0.0924	0.000014	0
24	23	6	0	23	0.092414	0.0924	0.000014	0
30	29	2	1	29	0.052014	0.0520	0.000014	0
36	35	6	1	35	0.052014	0.0520	0.000014	0
42	41	6	1	41	0.052014	0.0520	0.000014	0
48	47	-	-	41	0.052329	0.0520	0.000329	0
54	53	6	1	53	0.092414	0.0924	0.000014	0
60	59	-	-	53	0.092729	0.0924	0.000329	0
66	65	6	2	53	0.094297	0.0924	0.001897	0
72	71	6	2	53	0.092696	0.0924	0.0062[illegible]	[illegible]
78	77	6	2	53	0.108310	0.0924	0.015[illegible]	[illegible]
84	83	6	2	53	0.430000	0.0924	0.337[illegible]	[illegible]
90	89	2	0	89	0.052074	0.0520	0.000[illegible]	[illegible]
96	95	6	0	95	0.054732	0.0520	0.000[illegible]	[illegible]
102	101	6	0	101	0.061394	0.0520	0.000014	0.009380
108	107	6	0	107	0.122814	0.0924	0.000014	0.030400
114	113	6	0	113	0.027104	0.0924	0.000014	0.034690
120	119	2	1	119	0.052014	0.0520	0.000014	0
126	125	6	1	125	0.052014	0.0520	0.000014	0
132	131	6	1	131	0.052014	0.0520	0.000014	0
138	137	6	3	119	0.092696	0.0924	0.006296	0
144	143	6	3	119	0.108310	0.0924	0.015910	0
150	149	2	2	149	0.052014	0.0520	0.000014	0

$$\varepsilon_{fc} \equiv \frac{a}{2}\left(t - t_{UDRE} + t_{lat}\right)^2$$

$$\varepsilon_{rrc} \equiv \left(\frac{a\, I_{fc}}{4} + \frac{B_{rrc}}{t_n - t_o}\right)(t - t_n)$$

The receipt of MT 6 (with IODF<3) is equivalent to another reception of last fast correction

UDRE Time-Out

$t - t_{UDRE} > 13$

$$PRC(t) = PRC_n + RRC_n (t - t_n)$$

$$RRC_n = \frac{PRC_n - PRC_o}{t_n - t_o}$$

RRC Time-Out

$$\Delta t = t_n - t_o > I_{fc}$$

$$t - t_n > 8\Delta t$$

PRC Time-Out

$$t - t_{UDRE} > I_{fc} + 1$$

Ifc=66sec

Manuel Hernández-Pajares, J. Miguel Juan, Jaume Sanz, Xavier Prats, February 2002.

$$\sigma^2_{i,flt} = \sigma^2_{UDRE} + \varepsilon^2_{fc} + \varepsilon^2_{rrc} + \varepsilon^2_{ltc} + \varepsilon^2_{er}$$

Time t (s)	Last Mes t2, t6 (s)	Last Mess Type	Last Mes IODF	t_{UDRE}	σ^2_{flt}	σ^2_{UDRE}	ε^2_{fc}	ε^2_{rrc}
0	-1	2	0	-1	0.052014	0.0520	0.000014	0
6	5	6	0	5	0.052014	0.0520	0.000014	0
12	11	6	0	11	0.052014	0.0520	0.000014	0
18	17	6	0	17	0.092414	0.0924	0.000014	0
24	23	6	0	23	0.092414	0.0924	0.000014	0
30	29	2	1	29	0.052014	0.0520	0.000014	0
36	35	6	1	35	0.052014	0.0520	0.000014	0
42	41	6	1	41	0.052014	0.0520	0.000014	0
48	47	-	-	41	0.052329	0.0520	0.000329	0
54	53	6	1	53	0.092414	0.0924	0.000014	0
60	59	-	-	53	0.092729	0.0924	0.000329	0
66	65	6	2	53	0.094297	0.0924	0.001897	0
72	71	6	2	53	0.092696	0.0924	0.0062[illegible]	[illegible]
78	77	6	2	53	0.108310	0.0924	0.015[illegible]	[illegible]
84	83	6	2	53	0.430000	0.0924	0.337[illegible]	[illegible]
90	89	2	0	89	0.052074	0.0520	0.000[illegible]	[illegible]
96	95	6	0	95	0.054732	0.0520	0.000[illegible]	[illegible]
102	101	6	0	101	0.061394	0.0520	0.000014	0.009380
108	107	6	0	107	0.122814	0.0924	0.000014	0.030400
114	113	6	0	113	0.027104	0.0924	0.000014	0.034690
120	119	2	1	119	0.052014	0.0520	0.000014	0
126	125	6	1	125	0.052014	0.0520	0.000014	0
132	131	6	1	131	0.052014	0.0520	0.000014	0
138	137	6	3	119	0.092696	0.0924	0.006296	0
144	143	6	3	119	0.108310	0.0924	0.015910	0
150	149	2	2	149	0.052014	0.0520	0.000014	0

$$\varepsilon_{fc} \equiv \frac{a}{2}\left(t - t_{UDRE} + t_{lat}\right)^2$$

$$\varepsilon_{rrc} \equiv \left(\frac{a\, I_{fc}}{4} + \frac{B_{rrc}}{t_n - t_o}\right)(t - t_n)$$

MT 6 is missed and t_{UDRE} remains at 41s, inflating the ε^2_{fc} term

UDRE Time-Out
$t - t_{UDRE} > 13$

$$PRC(t) = PRC_n + RRC_n (t - t_n)$$

$$RRC_n = \frac{PRC_n - PRC_o}{t_n - t_o}$$

RRC Time-Out

$$\Delta t = t_n - t_o > I_{fc}$$

$$t - t_n > 8\Delta t$$

PRC Time-Out

$$t - t_{UDRE} > I_{fc} + 1$$

Ifc=66sec

$$\sigma^2_{i,flt} = \sigma^2_{UDRE} + \varepsilon^2_{fc} + \varepsilon^2_{rrc} + \varepsilon^2_{ltc} + \varepsilon^2_{er}$$

$$\varepsilon_{fc} \equiv \frac{a}{2}\left(t - t_{UDRE} + t_{lat}\right)^2$$

$$\varepsilon_{rrc} \equiv \left(\frac{a\, I_{fc}}{4} + \frac{B_{rrc}}{t_n - t_o}\right)\left(t - t_n\right)$$

Time t (s)	Last Mes t2, t6 (s)	Last Mess Type	Last Mes IODF	t_{UDRE}	σ^2_{flt}	σ^2_{UDRE}	ε^2_{fc}	ε^2_{rrc}
0	-1	2	0	-1	0.052014	0.0520	0.000014	0
6	5	6	0	5	0.052014	0.0520	0.000014	0
12	11	6	0	11	0.052014	0.0520	0.000014	0
18	17	6	0	17	0.092414	0.0924	0.000014	0
24	23	6	0	23	0.092414	0.0924	0.000014	0
30	29	2	1	29	0.052014	0.0520	0.000014	0
36	35	6	1	35	0.052014	0.0520	0.000014	0
42	41	6	1	41	0.052014	0.0520	0.000014	0
48	47	-	-	41	0.052329	0.0520	0.000329	0
54	53	6	1	53	0.092414	0.0924	0.000014	0
60	59		-	53	0.092729	0.0924	0.000329	0
66	65	6	2	53	0.094297	0.0924	0.001897	0
72	71	6	2	53	0.092696	0.0924	0.006[illegible]	[illegible]
78	77	6	2	53	0.108310	0.0924	0.015[illegible]	[illegible]
84	83	6	2	53	0.430000	0.0924	0.337[illegible]	[illegible]
90	89	2	0	89	0.052074	0.0520	0.000[illegible]	[illegible]
96	95	6	0	95	0.054732	0.0520	0.000[illegible]	[illegible]
102	101	6	0	101	0.061394	0.0520	0.000014	0.009380
108	107	6	0	107	0.122814	0.0924	0.000014	0.030400
114	113	6	0	113	[illegible]	0.0924	0.000014	0.034690
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]00014	0
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]00014	0
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]00014	0
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]06296	0
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]15910	0
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]00014	0

IODF out of sequence, t_{UDRE} will remain at 53s until the receip of the next fast correction

UDRE Time-Out
$t-t_6>13$

$$PRC(t) = PRC_n + RRC_n(t - t_n)$$

$$RRC_n = \frac{PRC_n - PRC_o}{t_n - t_o}$$

$RRC\ Time-Out$

$\Delta t = t_n - t_o > I_{fc}$

$t - t_n > 8\Delta t$

$PRC\ Time-Out$

$t - t_{UDRE} > I_{fc} + 1$

Ifc=66sec

NOTE: Because the IODF was not set to 3 and the user has not missed 4 messages in row, they know that the service provided is monitoring this and other combinations of old data and it is save for them to continue it use.

Thence, it is using $t-t_6>13$, instead of $t-t_{UDRE}>13$ for UDRE Time-Out.

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$$\sigma^2_{i,flt} = \sigma^2_{UDRE} + \varepsilon^2_{fc} + \varepsilon^2_{rrc} + \varepsilon^2_{ltc} + \varepsilon^2_{er}$$

$$\varepsilon_{fc} \equiv \frac{a}{2}\left(t - t_{UDRE} + t_{lat}\right)^2$$

$$\varepsilon_{rrc} \equiv \left(\frac{a\, I_{fc}}{4} + \frac{B_{rrc}}{t_n - t_o}\right)(t - t_n)$$

Time t (s)	Last Mes t2, t6 (s)	Last Mess Type	Last Mes IODF	t_{UDRE}	σ^2_{flt}	σ^2_{UDRE}	ε^2_{fc}	ε^2_{rrc}
0	-1	2	0	-1	0.052014	0.0520	0.000014	0
6	5	6	0	5	0.052014	0.0520	0.000014	0
12	11	6	0	11	0.052014	0.0520	0.000014	0
18	17	6	0	17	0.092414	0.0924	0.000014	0
24	23	6	0	23	0.092414	0.0924	0.000014	0
30	29	2	1	29	0.052014	0.0520	0.000014	0
36	35	6	1	35	0.052014	0.0520	0.000014	0
42	41	6	1	41	0.052014	0.0520	0.000014	0
48	47	-	-	47	0.052329	0.0520	0.00032	[illegible]
54	53	6	1	53	0.092414	0.0924	0.00001	[illegible]
60	59		-	53	0.092729	0.0924	0.00032	[illegible]
66	65	6	2	53	0.094297	0.0924	0.00189	[illegible]
72	71	6	2	53	0.092696	0.0924	0.006296	0
78	77	6	2	53	0.108310	0.0924	0.015910	0
84	83	6	2	53	0.430000	0.0924	0.337600	0
90	89	2	0	89	0.052074	0.0520	0.000014	0.000060
96	95	6	0	95	0.054732	0.0520	0.000014	0.002720
102	101	6	0	101	0.061394	0.0520	0.000014	0.009380
108	107	6	0	107	0.122814	0.0924	0.000014	0.030400
114	113	6	0	113	0.027104	0.0924	0.000014	0.034690
120	119	2	1	119	0.052014	0.0520	0.000014	0
126	125	6	1	125	0.052014	0.0520	0.000014	0
132	131	6	1	131	0.052014	0.0520	0.000014	0
138	137	6	3	119	0.092696	0.0924	0.006296	0
144	143	6	3	119	0.108310	0.0924	0.015910	0
150	149	2	2	149	0.052014	0.0520	0.000014	0

The user is aware of a FC is missing.

RRC is formed using IODFs out of sequence => ε^2_{rrc}

$$PRC(t) = PRC_n + RRC_n(t - t_n)$$

$$RRC_n = \frac{PRC_n - PRC_o}{t_n - t_o}$$

RRC Time-Out

$$\Delta t = t_n - t_o > I_{fc}$$

$$t - t_n > 8\Delta t$$

PRC Time-Out

$$t - t_{UDRE} > I_{fc} + 1$$

UDRE Time-Out

$t - t_{UDRE} > 13$

Ifc=66sec

Manuel Hernández-Pajares, J. Miguel Juan, Jaume Sanz, Xavier Prats, February 2002.

$$\sigma^2_{i,flt} = \sigma^2_{UDRE} + \varepsilon^2_{fc} + \varepsilon^2_{rrc} + \varepsilon^2_{ltc} + \varepsilon^2_{er}$$

$$\varepsilon_{fc} \equiv \frac{a}{2}\left(t - 119 + t_{lat}\right)^2$$

$$IODF = 3; \quad if \left|\Delta t - I_{fc}/2\right| \neq 0$$

$$\varepsilon_{rrc} \equiv \left(\frac{a\left|\Delta t - I_{fc}/2\right|}{2} + \frac{B_{rrc}}{\Delta t}\right)(t - 119)$$

Time t (s)	Last Mes t2, t6 (s)	Last Mess Type	Last Mes IODF	t_{UDRE}	σ^2_{flt}	σ^2_{UDRE}	ε^2_{fc}	ε^2_{rrc}
0	-1	2	0	-1	0.052014	0.0520	0.000014	0
6	5	6	0	5	0.052014	0.0520	0.000014	0
12	11	6	0	11	0.052014	0.0520	0.000014	0
18	17	6	0	17	0.092414	0.0924	0.000014	0
24	23	6	0	23	0.092414	0.0924	0.000014	0
30	29	2	1	29	0.052014	0.0520	0.000014	0
36	35	6	1	35	0.052014	0.0520	0.000014	0
42	41	6	1	41	0.052014	0.0520	0.000014	0
48	47	-	-	47	0.052329	0.0520	0.000329	0
54	53	6	1	53	0.092414	0.0924	0.000014	0
60	59	[redacted]	-	53	0.092729	0.0924	0.000	
						0924	0.0018	
						0924	0.006	
						0924	0.015	
						0924	0.337	
90	89	2	0	89	0.052074	0.0520	0.000014	0.000060
96	95	6	0	95	0.054732	0.0520	0.000014	0.002720
102	101	6	0	101	0.061394	0.0520	0.000014	0.009380
108	107	6	0	107	0.122814	0.0924	0.000014	0.030400
114	113	6	0	113	0.027104	0.0924	0.000014	0.034690
120	119	2	1	119	0.052014	0.0520	0.000014	0
126	125	6	1	125	0.052014	0.0520	0.000014	0
132	131	6	1	131	0.052014	0.0520	0.000014	0
138	137	6	3	119	0.092696	0.0924	0.006296	0
144	143	6	3	119	0.108310	0.0924	0.015910	0
150	149	2	2	149	0.052014	0.0520	0.000014	0

NOTE:
When IODF in either message is set to 3, then $t_{UDRE}=t_n$ and is not updated to the time of MT6

Alarm Condition (IODF=3)
t_{UDRE} backs to 119 (the last received Fast Correction)

UDRE Time-Out
$t-t_6>13$

$$PRC(t) = PRC_n + RRC_n(t - t_n)$$

$$RRC_n = \frac{PRC_n - PRC_o}{t_n - t_o}$$

$RRC\ Time-Out$
$\Delta t = t_n - t_o > I_{fc}$
$t - t_n > 8\Delta t$

$PRC\ Time-Out$
$t - 119 > I_{fc} + 1$

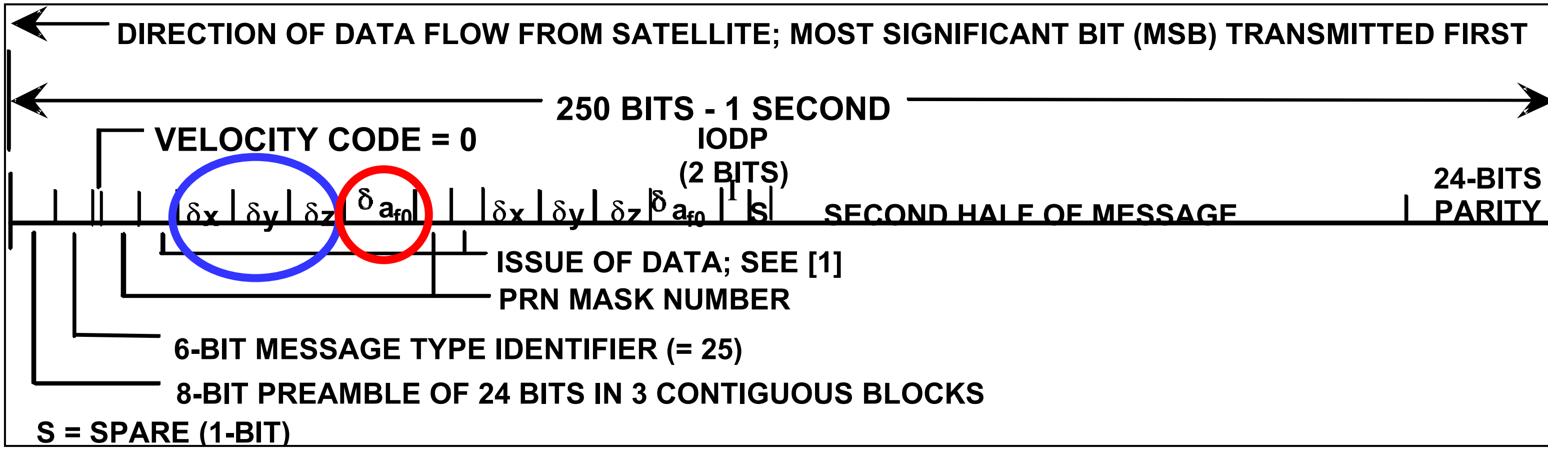
Ifc=66sec

Manuel Hernández-Pajares, J. Miguel Juan, Jaume Sanz, Xavier Prats, February 2002.

Long-Term Corrections (MT25, 24)

- Primarily Correct Ephemeris Errors
  - Also removes Slowly Varying Clock
  - And discontinuities in Broadcast Ephemeris
  - Separate Degradation Factors for Lost Messages
- For GEO are contained in MT9

Long-Term Corrections (MT25)



$$\begin{bmatrix}\delta x(t)\\ \delta y(t)\\ \delta z(t)\end{bmatrix} = \begin{bmatrix}\delta x_0\\ \delta y_0\\ \delta z_0\end{bmatrix} + \begin{bmatrix}\delta \dot{x}_0\\ \delta \dot{y}_0\\ \delta \dot{z}_0\end{bmatrix}(t - t_0) \rightarrow \begin{bmatrix}x\\ y\\ z\end{bmatrix} = \begin{bmatrix}x_{GPS/GLONASS}\\ y_{GPS/GLONASS}\\ z_{GPS/GLONASS}\end{bmatrix} + \begin{bmatrix}\delta x\\ \delta y\\ \delta z\end{bmatrix}$$

$$\delta t(t) = \delta a_{f0} + \delta a_{f1}(t - t_0) + \delta a_{fG0} \rightarrow dt = dt_{GPS/GLONASS} + \delta t$$

GLONASS (MT12)

$$Y = C1 + PRC - \rho^* + dt^{sat} + rel - TGD + IONO + TROP$$

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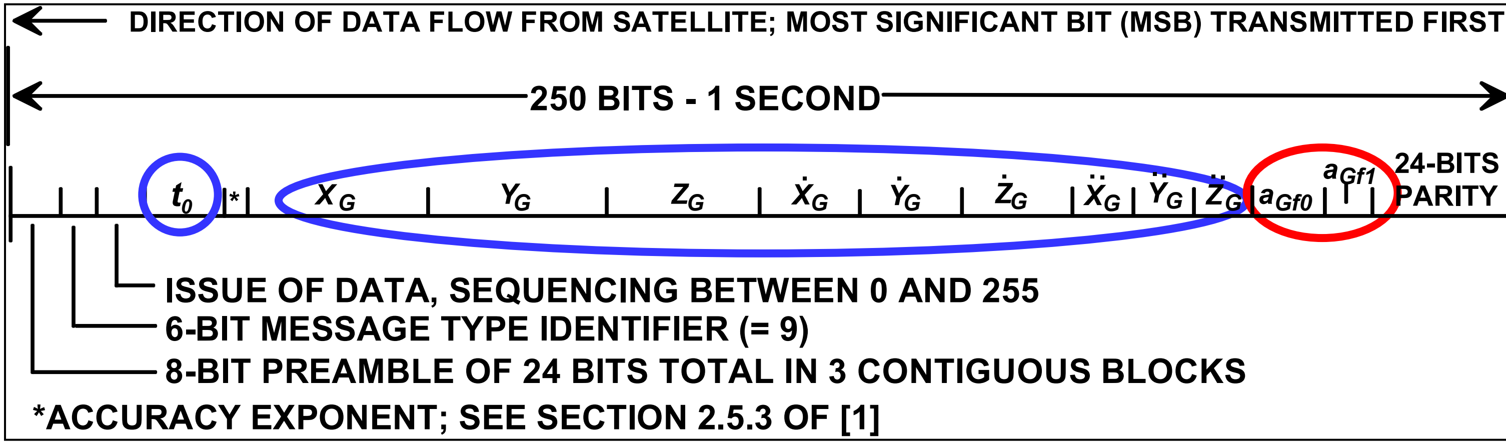
GEO Coordinates and clock (MT 9)



$$\begin{bmatrix} x(t) \\ y(t) \\ z(t) \end{bmatrix} = \begin{bmatrix} x_G \\ y_G \\ z_G \end{bmatrix} + \begin{bmatrix} \dot{x}_G \\ \dot{y}_G \\ \dot{z}_G \end{bmatrix} (t - t_0) + \frac{1}{2} \begin{bmatrix} \ddot{x}_G \\ \ddot{y}_G \\ \ddot{z}_G \end{bmatrix} (t - t_0)^2$$

$$dt(t) = \delta a_{Gf0} + \delta a_{Gf1} (t - t_0)$$

LONG-TERM DEGRADATION PARAMETER (GPS/GLONASS/GEO)

MT10

- GPS/GLONASS
  - vcode=1 (MT25, 24)

$$\varepsilon_{ltc} = \begin{cases} 0 & if\ t_0 < t < t_0 + I_{ltc\_v1} \\ C_{ltc\_lsb} + C_{ltc\_v1} \max\left(0, t_0 - t, t - t_0 - I_{ltc\_v1}\right) & otherwise \end{cases}$$

  - vcode=0 (MT25, 24)

$$\varepsilon_{ltc} = C_{ltc\_v0} \left\lfloor \frac{t - t_{ltc}}{I_{ltc\_v0}} \right\rfloor$$

- GEO

$$\varepsilon_{ltc} = \begin{cases} 0 & t_0 < t < t_0 + I_{geo} \\ C_{geo\_lsb} + C_{geo\_v} \max\left(0, t_0 - t, t - t_0 - I_{geo}\right) & otherwise \end{cases}$$

$$\sigma^2_{i,flt} = \sigma^2_{UDRE} + \varepsilon^2_{fc} + \varepsilon^2_{rrc} + \varepsilon^2_{ltc} + \varepsilon^2_{er}$$

En Route Through NPA Degradation

- For Precision Approach a user is only allowed to miss one of any particular message. However, the user can still operate in less stringent phases of flight even if they have missed two or any particular fast or slow correction messages.

$$\varepsilon_{er} = \begin{cases} 0 & \text{Neither fast nor long term corrections have time out for precision approach} \\ C_{er} & \text{Otherwise} \end{cases}$$

$$\sigma^2{}_{i,flt} = \sigma^2{}_{UDRE} + \varepsilon^2{}_{fc} + \varepsilon^2{}_{rrc} + \varepsilon^2{}_{ltc} + \varepsilon^2{}_{er}$$

Ephemeris + Clocks → Fast Corrections + Long Term Corrections + UDRE + Degradation Param.

MT1, MT2,5,24, MT6, MT25, MT7, MT12, MT9

MT10

IONO → IONO Corrections + GIVE + Degradation Param.

MT18
MT26

$$Y = C1 + PRC - \rho^{*} + \Delta t^{sat} + dt^{sat} + rel - TGD + IONO + TROP$$

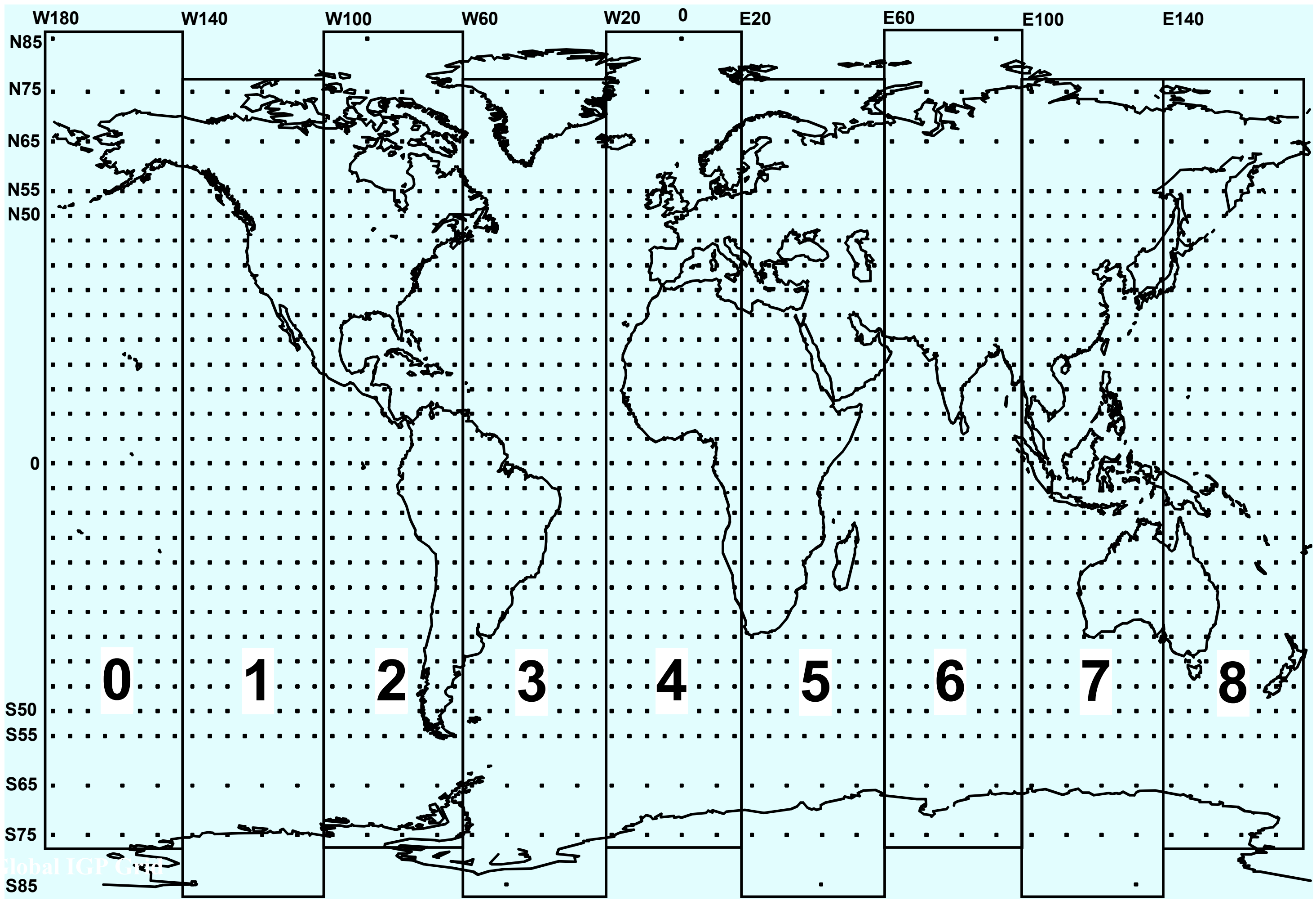
$$\sigma^2 = \sigma_{flt}^2 + \sigma_{UIRE}^2 + \sigma_{air}^2 + \sigma_{tropo}^2$$

Ionospheric Corrections (MT26)

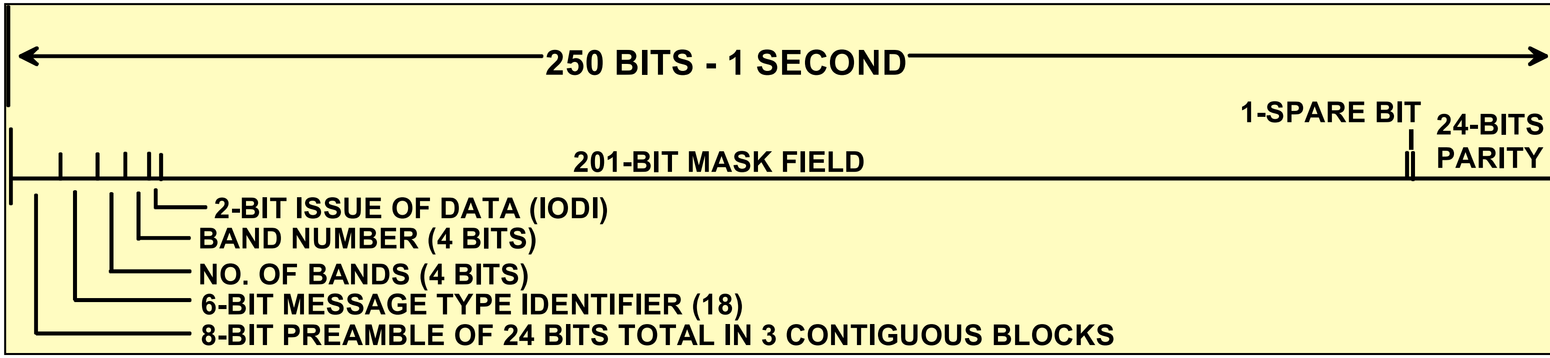
- Only Requiered for Precission Approach
  - Grid of Vertical Ionospheric Corrections
  - Users Select 3 o 4 IGPs that Surrounding IPP
    - 5ºx5º or 10ºx10º for 55º<Lat<55º
    - Only 10ºx10º for 55º<|Lat|<85º
    - Circular regions for |Lat|>85º
  - Vertical Correction and UIVE Interpoled to IPP
  - Both Converted to Slant by Obliquity Factor

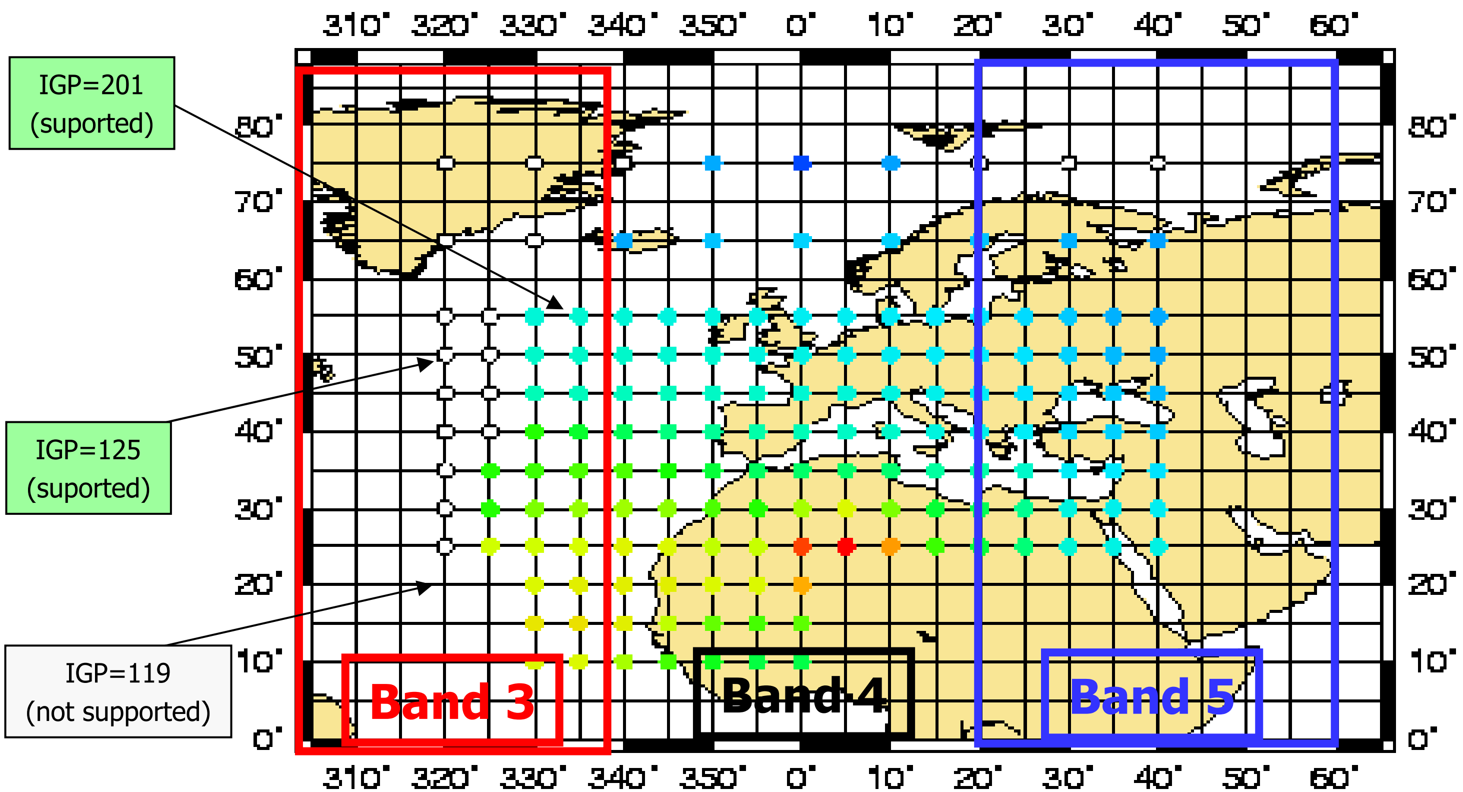
•IGP: Ionospheric Grid Point
•IPP: Ionospheric Pierce Point

GLOBAL IGP GRID



IGP MASK Message (MT18)





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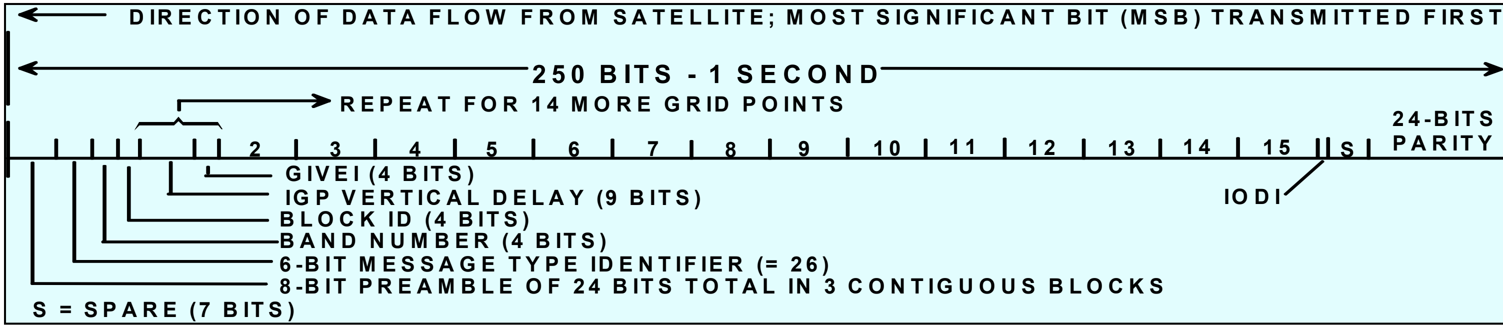
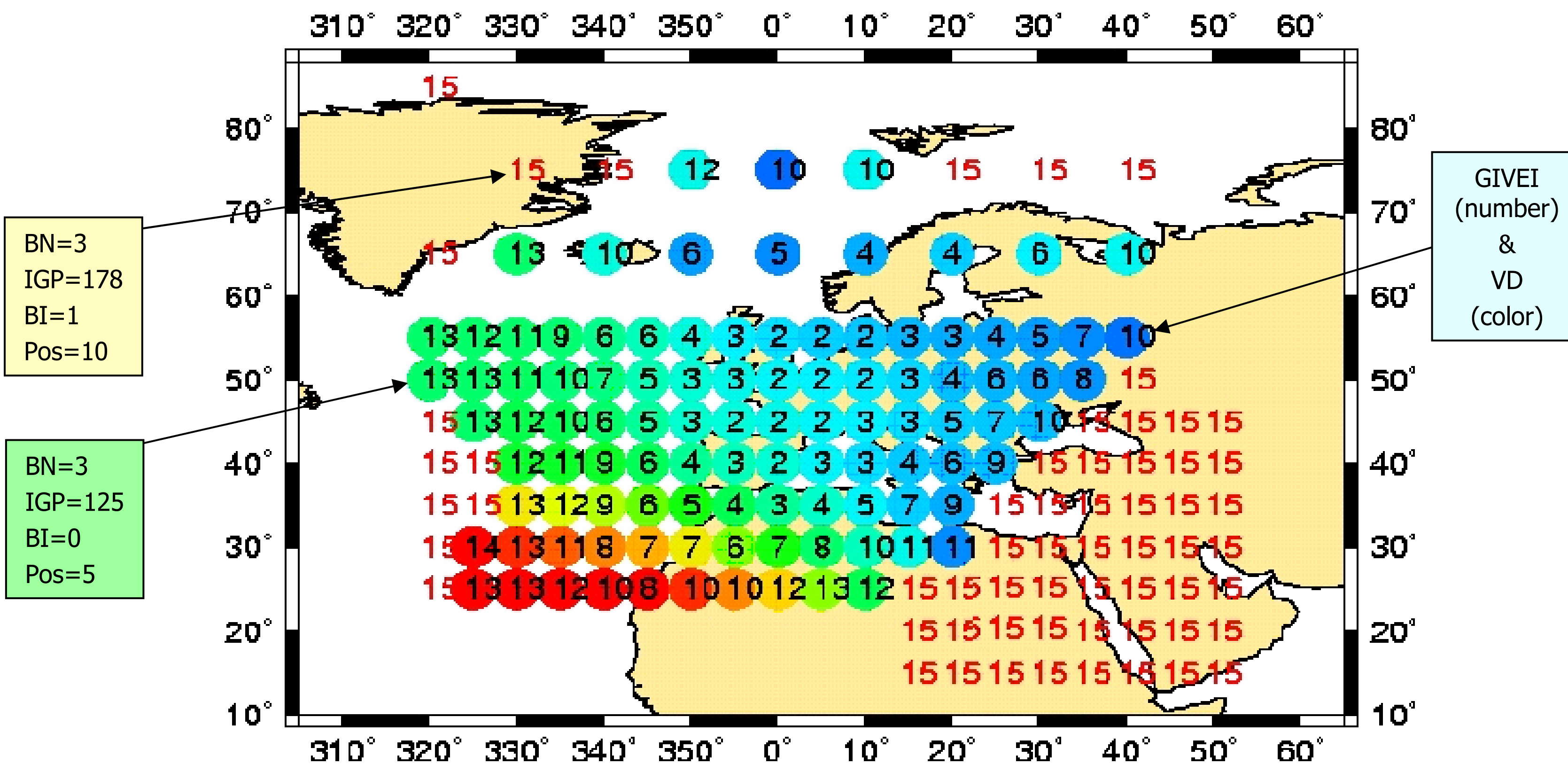
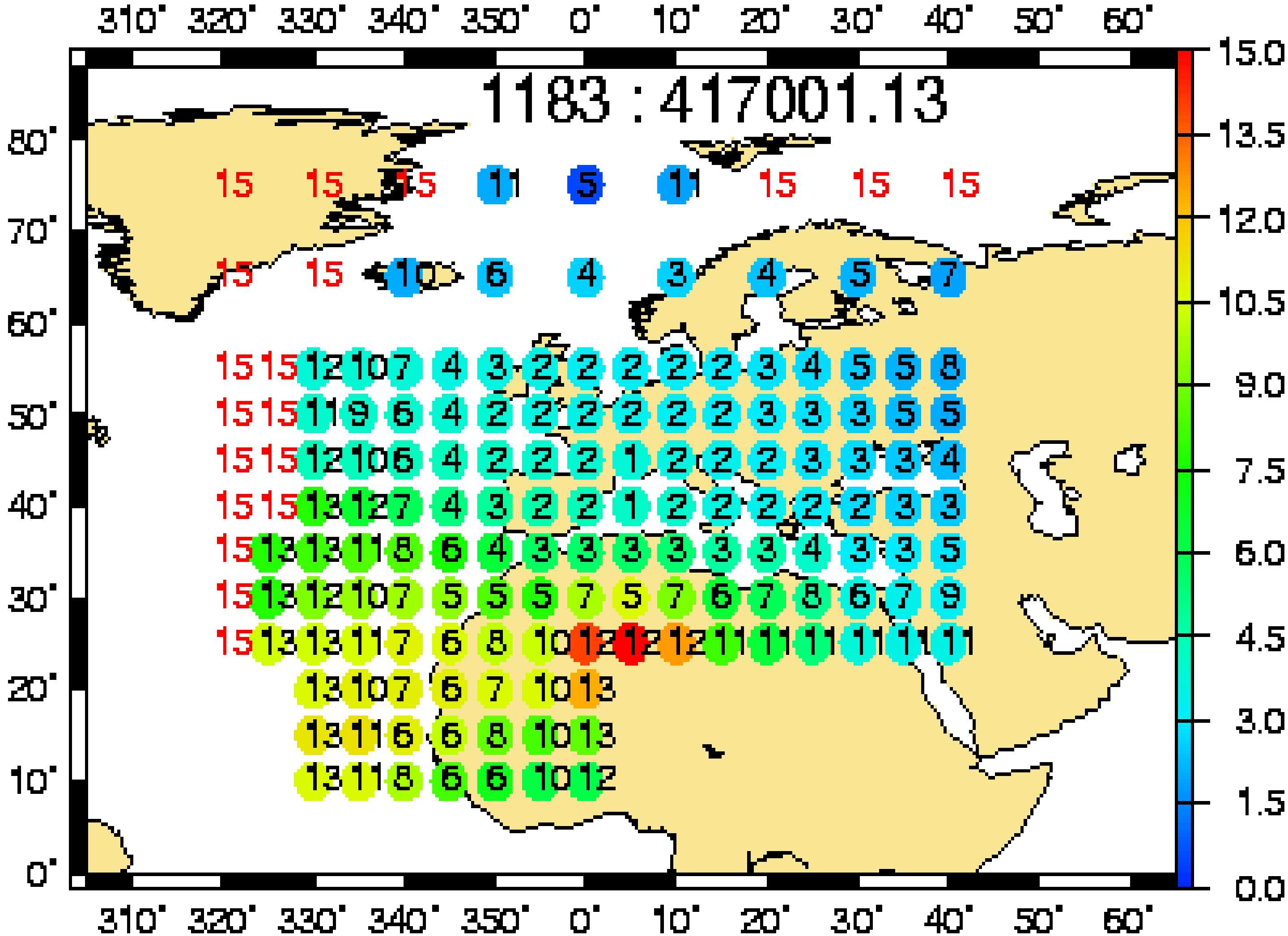
IONOSPHERIC DELAYS and BOUNDS (MT26)





Manuel Hernández-Pajares, J. Miguel Juan, Jaume Sanz, Xavier Prats, February 2002.

ESTB Sep 12th 2002



UPC

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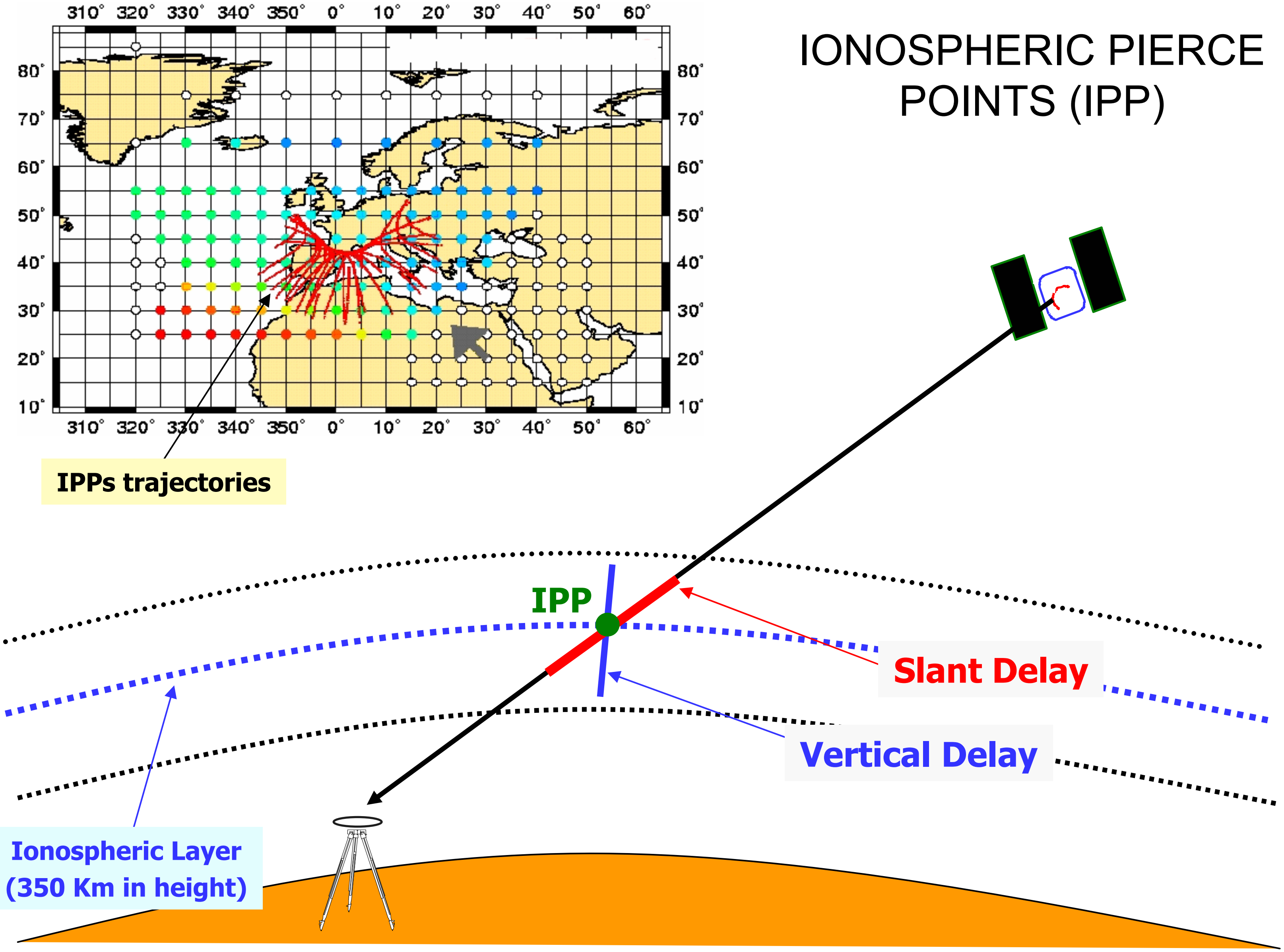
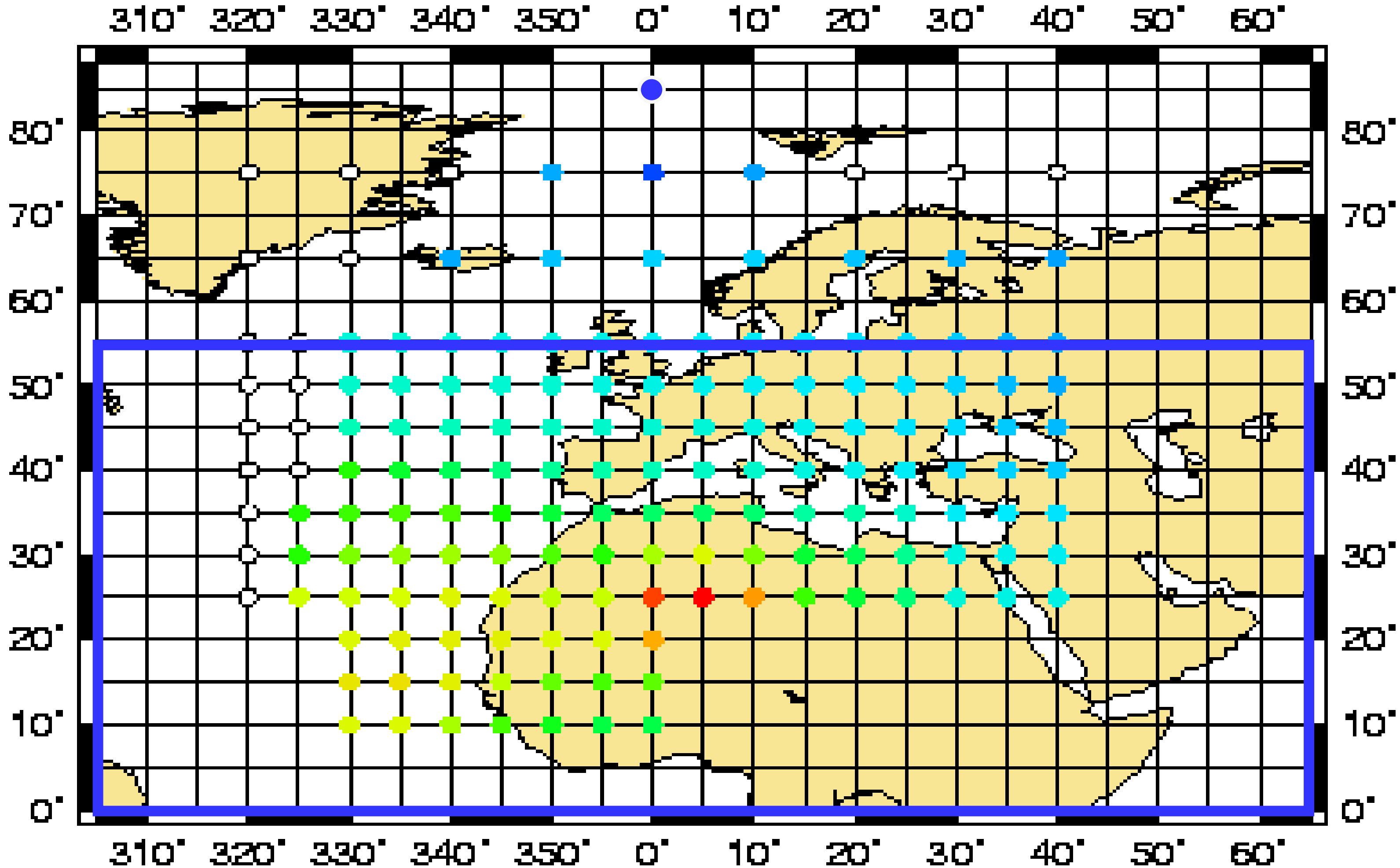
IONOSPHERIC PIERCE POINTS (IPP)



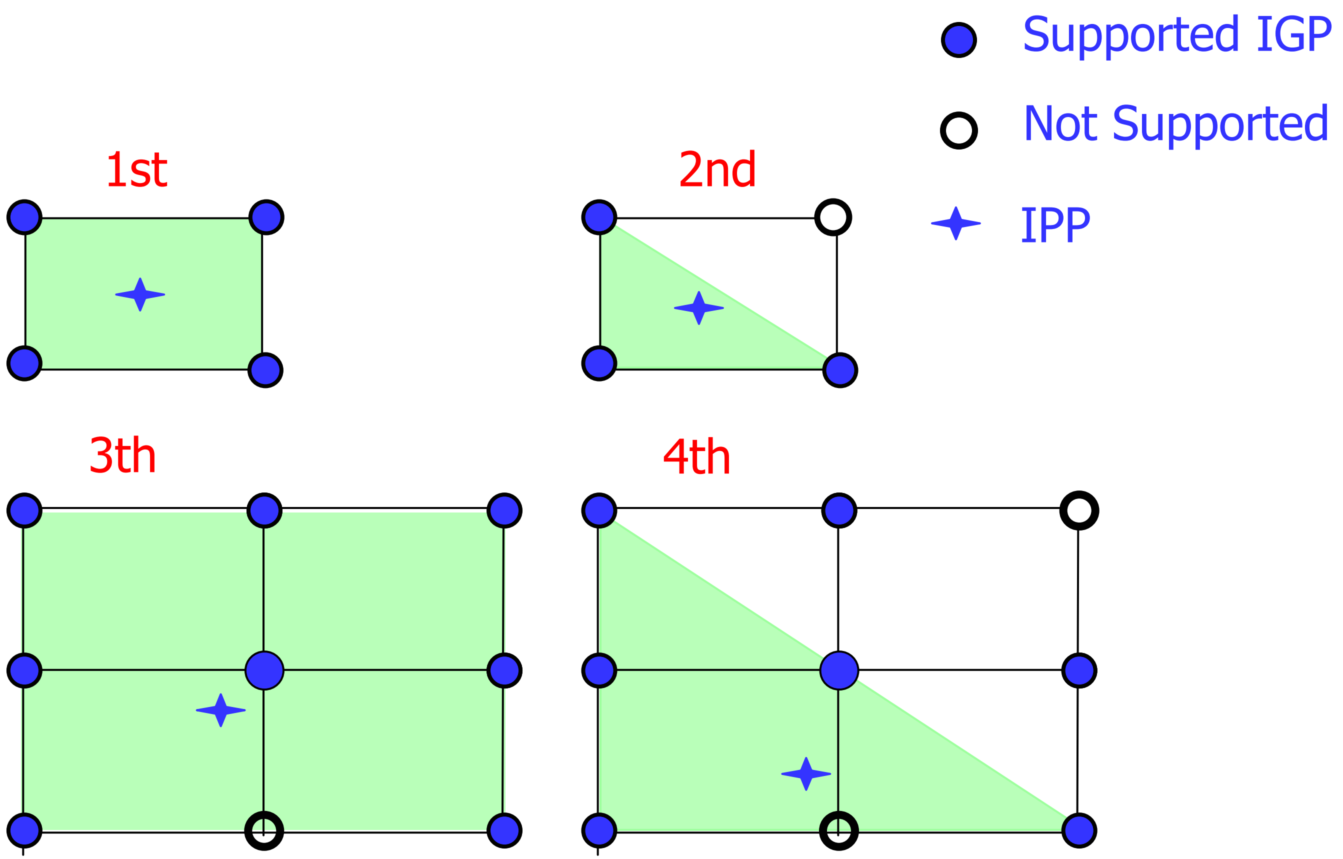
IGPs Selection Rules

- Four Distinct Grid Regions
  - First look for Surrounding Square Cell
  - Else Seek Surrounding Triangular Cell
  - If Neither Available for 5ºx5º look at 10ºx10º
  - From 75º to 85º Interpolate Using Virtual IGPs
  - No correction possible if Not Surrounded

|Lat| <= 55

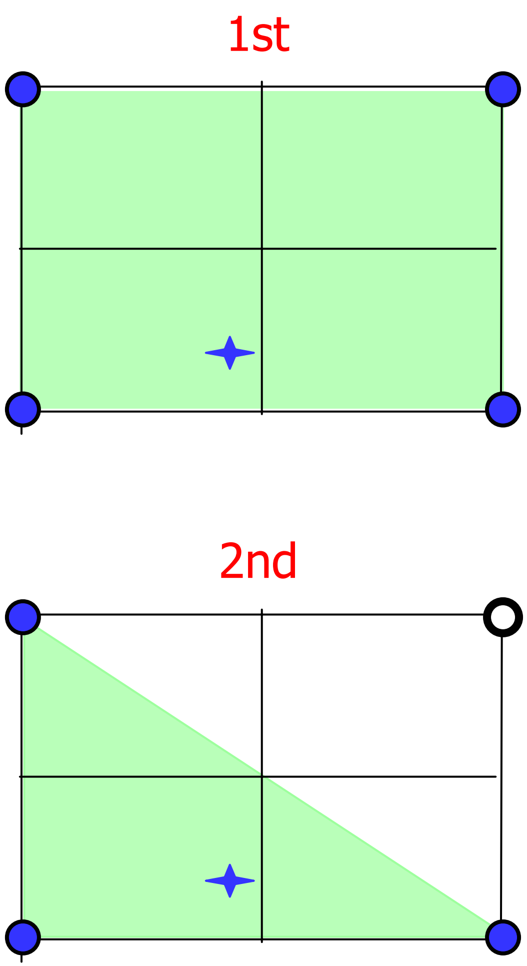


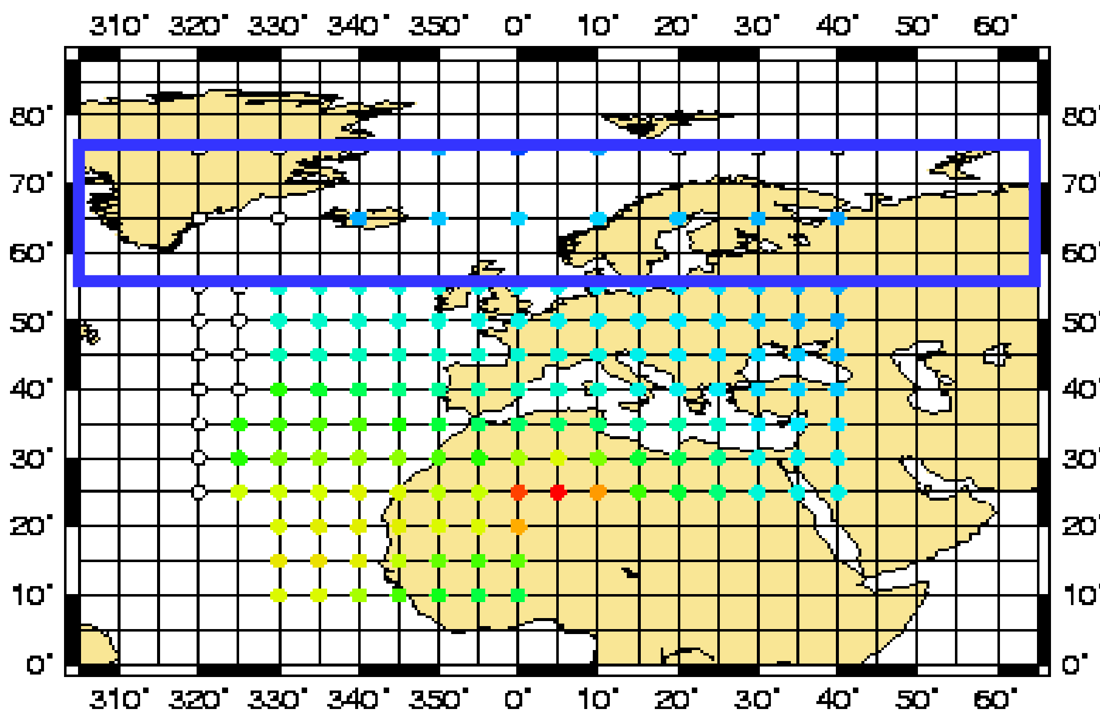
The selection of Interpolation Grid points |Lat| <= 55



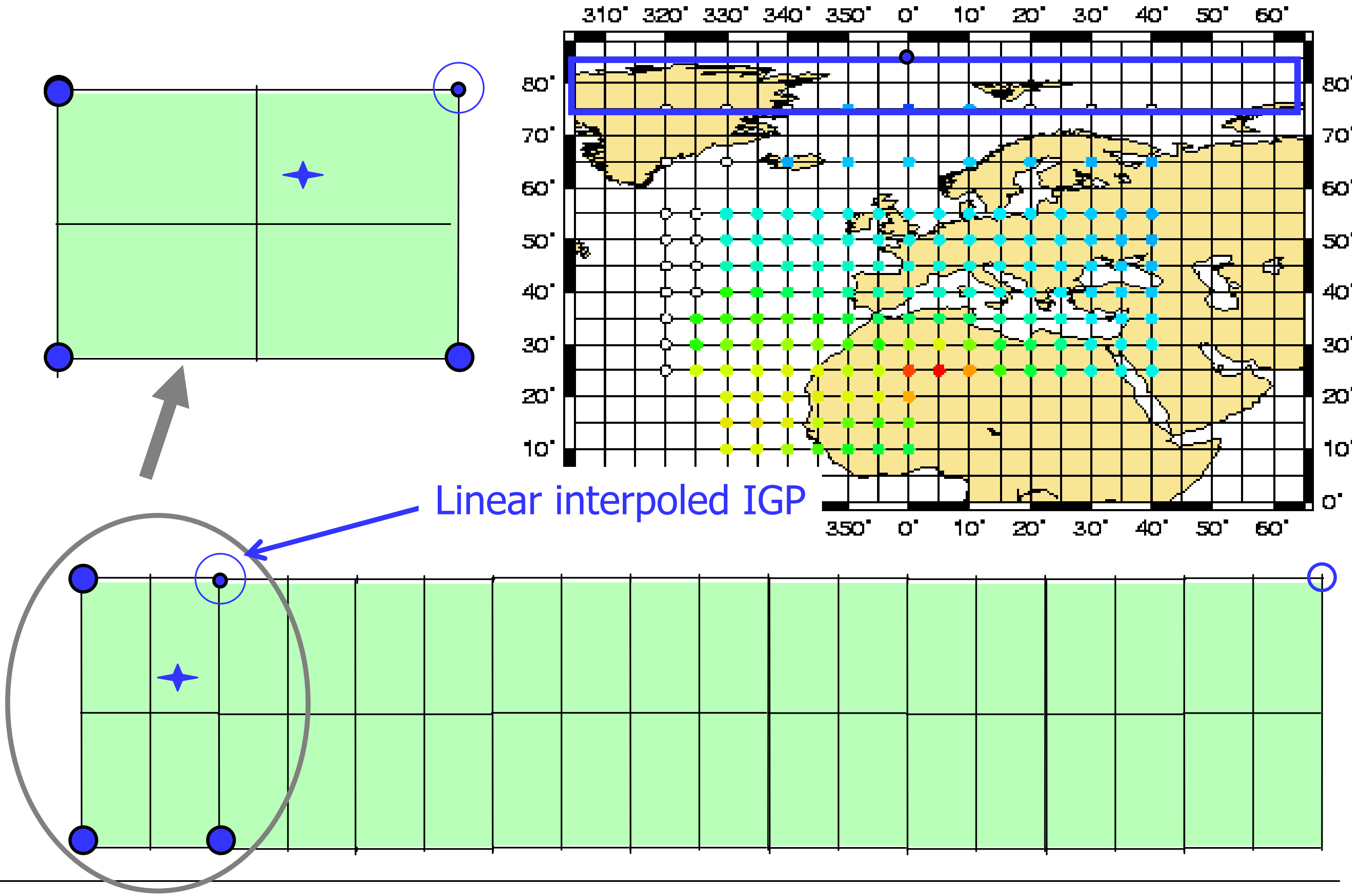
The selection of Interpolation Grid points 55<|Lat| <= 75

Supported IGP
Not Supported
IPP

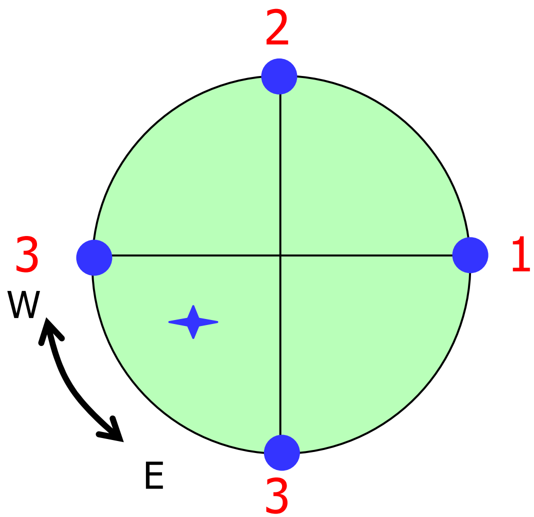


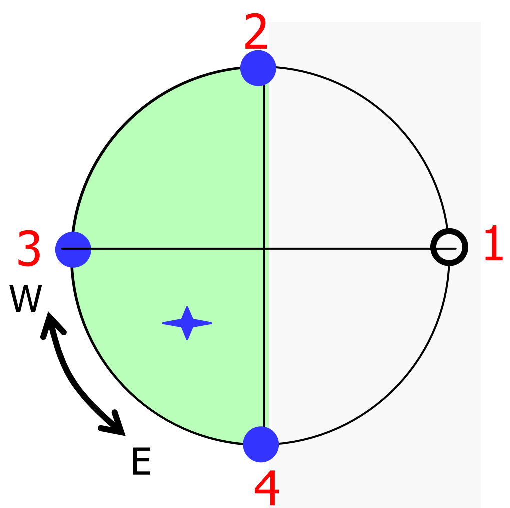


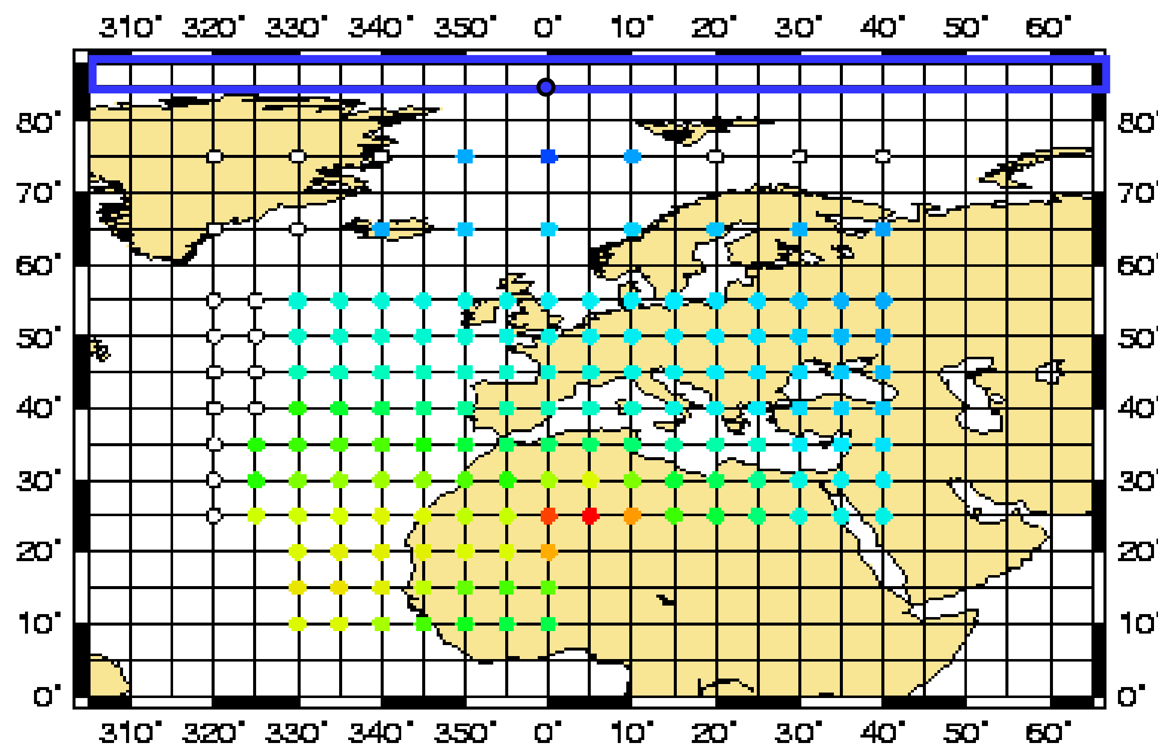
The selection of Interpolation Grid points
75<|Lat| <= 85



The selection of Interpolation Grid points 85<|Lat|







Ionospheric Delay Interpotation

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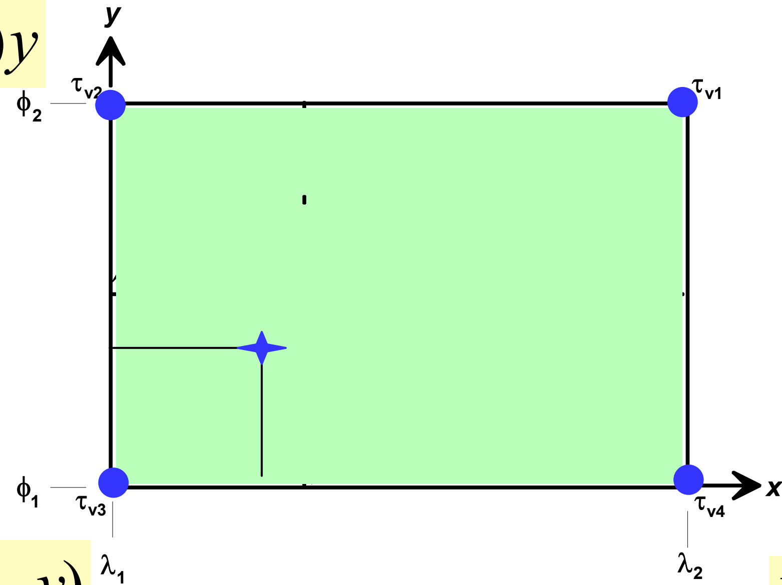
$$W_2 = (1-x)y$$

$$W_1 = xy$$



$$x = \frac{\lambda_{ipp} - \lambda_1}{\Delta\lambda}$$

$$y = \frac{\phi_{ipp} - \phi_1}{\Delta\phi}$$

$$W_3 = (1-x)(1-y)$$

$$W_4 = x(1-y)$$

$$\tau_{vpp}\left(\lambda_{pp}, \phi_{pp}\right) = \sum_{i=1}^{4} W_i(x_{pp}, y_{pp})\tau_{vi}$$

MT26

τ_{vi}

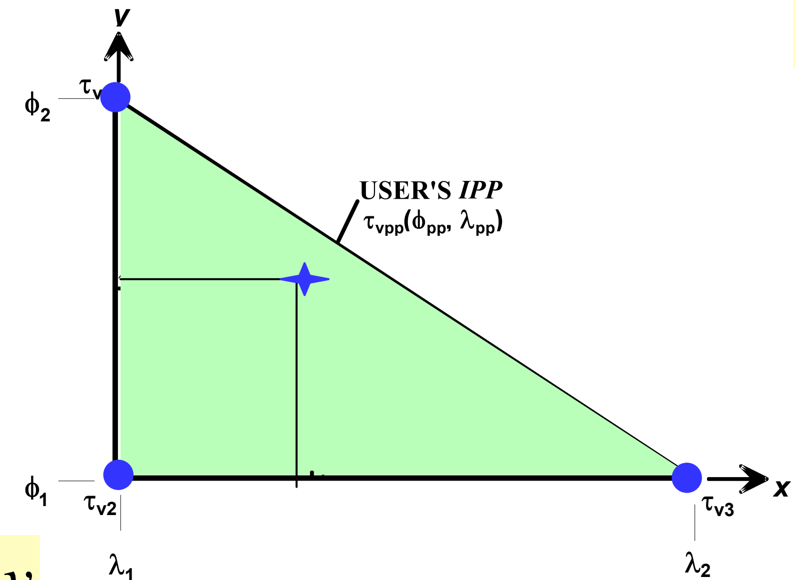
$$IC_i = -\tau_{spp}\left(\lambda_{pp}, \phi_{pp}\right) = -F_{pp} \cdot \tau_{vpp}\left(\lambda_{pp}, \phi_{pp}\right)$$

$$F_{pp} = \left[1 - \left(\frac{R_e \cos E}{R_e + h_I}\right)^2\right]^{-\frac{1}{2}}$$

Ionospheric Delay Interpotation

$W_2 = y$

$W_1 = 0$



$$x = \frac{\lambda_{ipp} - \lambda_1}{\Delta\lambda}$$

$$y = \frac{\phi_{ipp} - \phi_1}{\Delta\phi}$$

$W_3 = 1 - x - y$

$W_4 = x$

$$\tau_{vpp}\left(\lambda_{pp}, \phi_{pp}\right) = \sum_{i=1}^{4} W_i(x_{pp}, y_{pp})\tau_{vi}$$

MT26

τ_{vi}

$$IC_i = -\tau_{spp}\left(\lambda_{pp}, \phi_{pp}\right) = -F_{pp} \cdot \tau_{vpp}\left(\lambda_{pp}, \phi_{pp}\right)$$

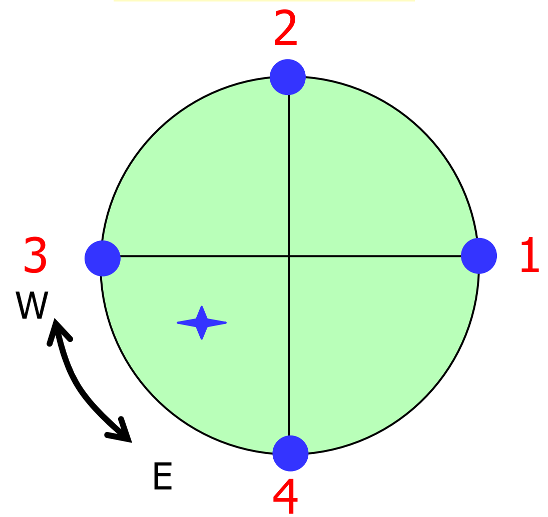
$$F_{pp} = \left[1 - \left(\frac{R_e \cos E}{R_e + h_I}\right)^2\right]^{-\frac{1}{2}}$$

Manuel Hernández-Pajares, J. Miguel Juan, Jaume Sanz, Xavier Prats, February 2002.

Ionospheric Delay Interpotation

$$W_2 = (1-x)y$$

$$W_3 = (1-x)(1-y)$$



$$W_1 = xy$$

$$W_4 = x(1-y)$$

$$y = \frac{|\phi_{ipp} - 85^o|}{10^o}$$

$$x = \frac{\lambda_{ipp} - \lambda_3}{90^o}(1-2y) + y$$

$$\tau_{vpp}\left(\lambda_{pp}, \phi_{pp}\right) = \sum_{i=1}^{4} W_i(x_{pp}, y_{pp})\tau_{vi}$$

MT26

τ_{vi}

$$IC_i = -\tau_{spp}\left(\lambda_{pp}, \phi_{pp}\right) = -F_{pp} \cdot \tau_{vpp}\left(\lambda_{pp}, \phi_{pp}\right)$$

$$F_{pp} = \left[1 - \left(\frac{R_e \cos E}{R_e + h_I}\right)^2\right]^{-\frac{1}{2}}$$

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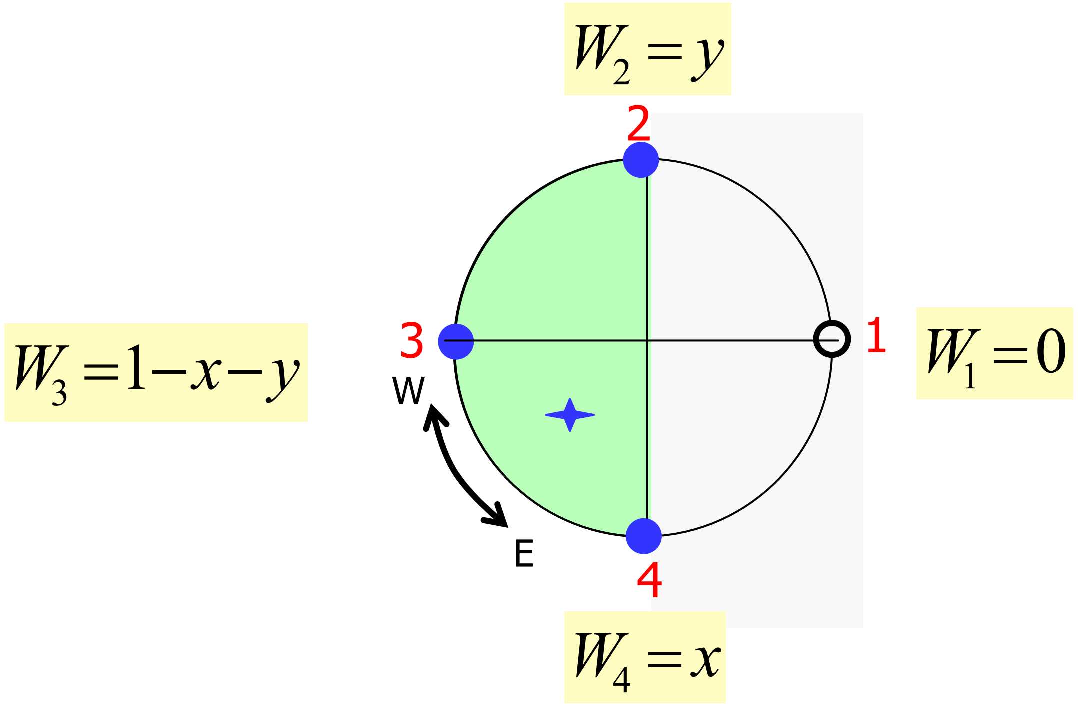
Ionospheric Delay Interpotation



$$y = \frac{|\phi_{ipp} - 85^o|}{10^o}$$

$$x = \frac{\lambda_{ipp} - \lambda_3}{90^o}(1 - 2y) + y$$

$$\tau_{vpp}(\lambda_{pp}, \phi_{pp}) = \sum_{i=1}^{4} W_i(x_{pp}, y_{pp})\tau_{vi}$$

MT26

τ_{vi}

$$IC_i = -\tau_{spp}(\lambda_{pp}, \phi_{pp}) = -F_{pp} \cdot \tau_{vpp}(\lambda_{pp}, \phi_{pp})$$

$$F_{pp} = \left[1 - \left(\frac{R_e \cos E}{R_e + h_I}\right)^2\right]^{-\frac{1}{2}}$$

Degradation of Ionospheric Corrections

$$\sigma_{UIRE}^2 = F_{pp}^2 \sigma_{UIVE}^2$$

$$F_{pp} = \left[1 - \left(\frac{R_e \cos E}{R_e + h_I}\right)^2\right]^{-\frac{1}{2}}$$

$$\sigma_{UIVE}^2 = \sum_{n=1}^{N} W_n\left(x_{pp}, y_{pp}\right)\sigma_{n,ionogrid}^2 \,, \quad N = 4\, or\, 3$$

$$\sigma^2{}_{ionogrid} = \begin{cases} \left(\sigma_{GIVE} + \varepsilon_{iono}\right)^2, & if \quad RSS_{iono} = 0 \quad (MT10) \\ \sigma^2{}_{GIVE} + \varepsilon^2{}_{iono}, & if \quad RSS_{iono} = 1 \quad (MT10) \end{cases}$$

$$\varepsilon_{iono} = C_{iono\_step}\, floor\left(\frac{t - t_{iono}}{I_{iono}}\right) + C_{iono\_ramp}\left(t - t_{iono}\right)$$

MT10

$B_{rrc}, C_{ltc\_lsb}, C_{ltc\_v1},$
$I_{ltc\_v1}, C_{ltc\_v0}, I_{ltc\_v0},$
$C_{er}, RSS_{UDRE},$
$C_{iono\_ramp}, C_{iono\_step},$
I_{iono}, RSS_{iono}

MT26

$t_{iono}, GIVE_i$

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UPC

SBAS
Performances

GNSS Performance Requirements

Flight Phase	Accuracy (H) 95%	Accuracy (V) 95%	Alert Limit (H)	Alert Limit (V)	Integrity	Time to alert	Continuity	Avail-ability	Associated RNP type(s
ENR	3.7 Km (2.0 NM)	N/A	7400 m 3700 m 1850 m	N/A	$1\text{-}10^{-7}$/h	5 min.	$1\text{-}10^{-4}$/h to $1\text{-}10^{-8}$/h	0.99 to 0.99999	20 to 10
TMA	0.74 Km (0.4 NM)	N/A	1850 m	N/A	$1\text{-}10^{-7}$/h	15 s	$1\text{-}10^{-4}$/h to $1\text{-}10^{-8}$/h	0.999 to 0.99999	5 to 1
NPA	220 m (720 ft)	N/A	600 m	N/A	1-10-7/h	10 s	1-10-4/h to 1-10-8/h	0.99 to 0.99999	0.5 to 0.3
APV-I	220 m (720 ft)	20 m (66 ft)	600 m	50 m	1-2x10-7 per approach	10 s	1-8x10-6 in any 15 s	0.99 to 0.99999	0.3/125
APV-II	16.0 m (52 ft)	8.0 m (26 ft)	40 m	20 m	1-2x10-7 per approach	6 s	1-8x10-6 in any 15 s	0.99 to 0.99999	0.03/50
CAT-I	16.0 m (52 ft)	6.0 - 4.0 m (20 to 13 ft)	40 m	15 -10 m	1-2x10-7 per approach	6 s	1-8x10-6 in any 15 s	0.99 to 0.99999	0.02/40

ICAO's GNSS Standards and Recomendation Practices (SARPS)

INTEGRITY RISK REQUIREMENTS:

PA: Signal In Space
$2x10^{-7}$/approach
(150 sec)

Ground System
$1x10^{-7}$/approach
(150 sec)

- Failures GPS/GLONASS/GEO
- Corruption data thought GEO link
- Hard, soft and WANet failures

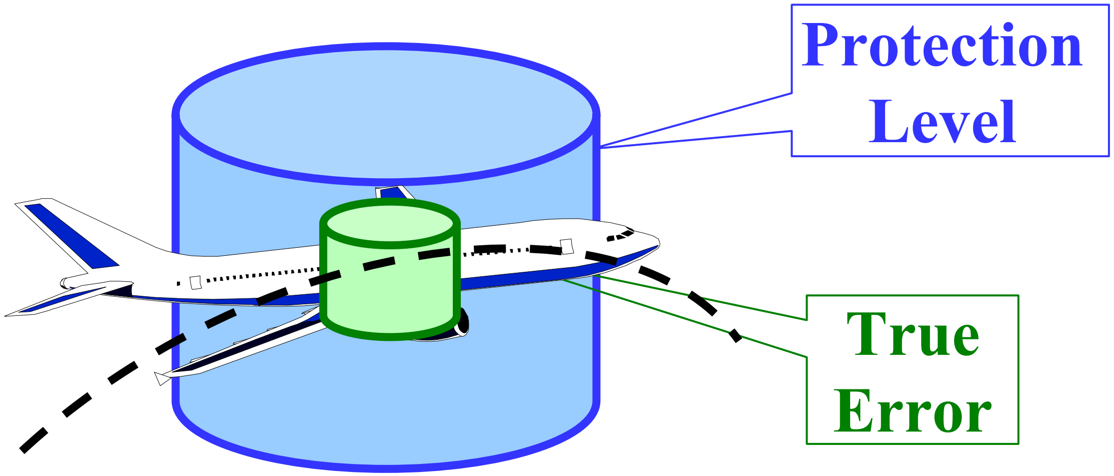
Fault Free Case
$1x10^{-7}$/approach
(150 sec)

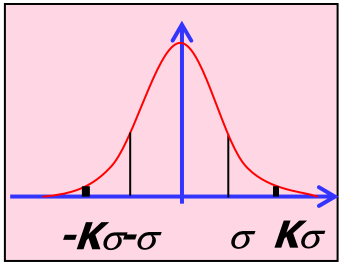
Induced by ground segment measurement data noise and algorithmic process (when no GPS/GLONASS/GEO sat failures, no ground segment/user equip failures)

HPL, VPL

PROTECTION LEVELS

To protect the user against misleading information (MI) due to data corrupted by the noise induced by the measurement and algorithmic process when the system is in a nominal state.





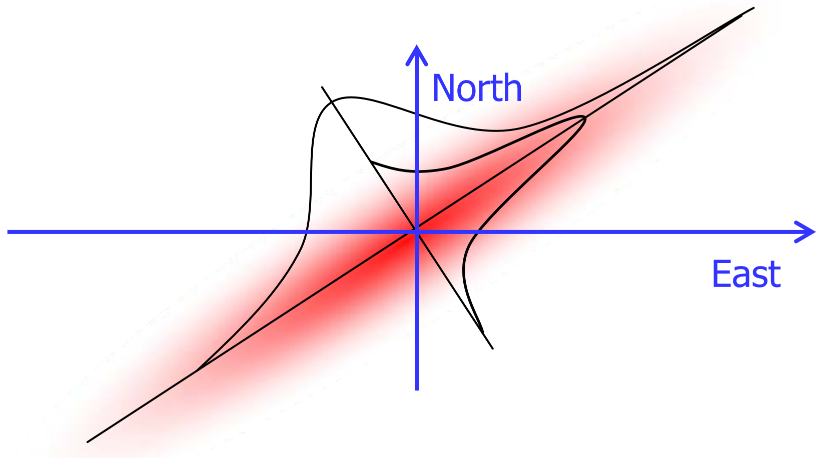
Tail area Probability

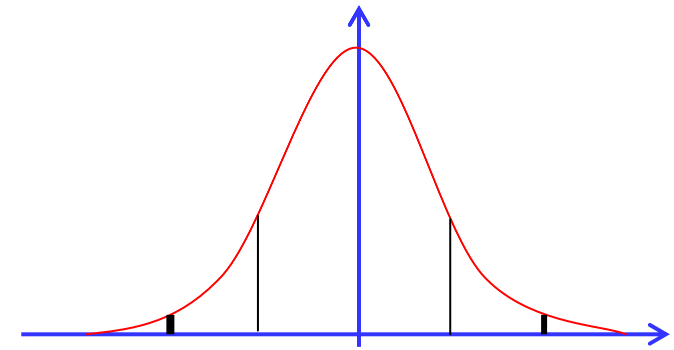
P(VPE>VPL) < 10^{-7} /sample

$$VPL = K_V \sqrt{\sum_{i=1}^{N} s_{V_i}^2 \sigma_i^2}$$

$$\sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i,UIRE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2$$

GEOMETRY





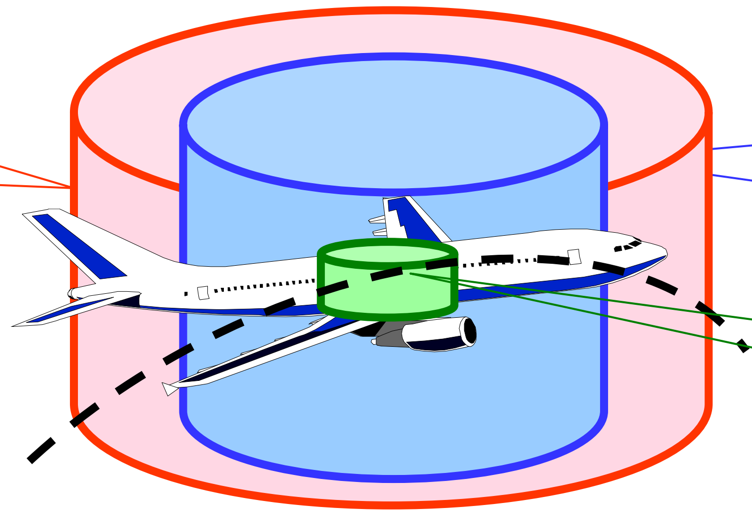
$$HPL = K_h d_{major} = K_h \sqrt{\frac{d_N^2 + d_{\grave{E}}^2}{2} + \sqrt{\frac{d_N^2 - d_{\grave{E}}^2}{2} + d_{NE}^2}}$$

$$VPL = K_v d_v$$

- **PA: SIS Integrity requirement: 2x10^{-7} /approach**
  - ➔ K_h=6.0, K_v=5.33 (Gaussian distrib.)
    - Only 1 indep sample per approach (150s)
    - A half of the total integrity allocated to **VPL (→ 10^{-7}/sample)**
    - HPL bounding prob. taken as negligible and only one dimension is used for **HPL (→ 10^{-9}/sample)**
- **En Route to NPA: SIS Integ. req. 1x10^{-7}/hour**
  - ➔ K_h= 6.18 (Rayleigh distrib.)
    - 10 indep samples per hour
    - A half of the total integrity allocated to **HPL**
    - Worst case assumption $d_{min}=d_{major}$ **(→ 5x10^{-9}/sample)**

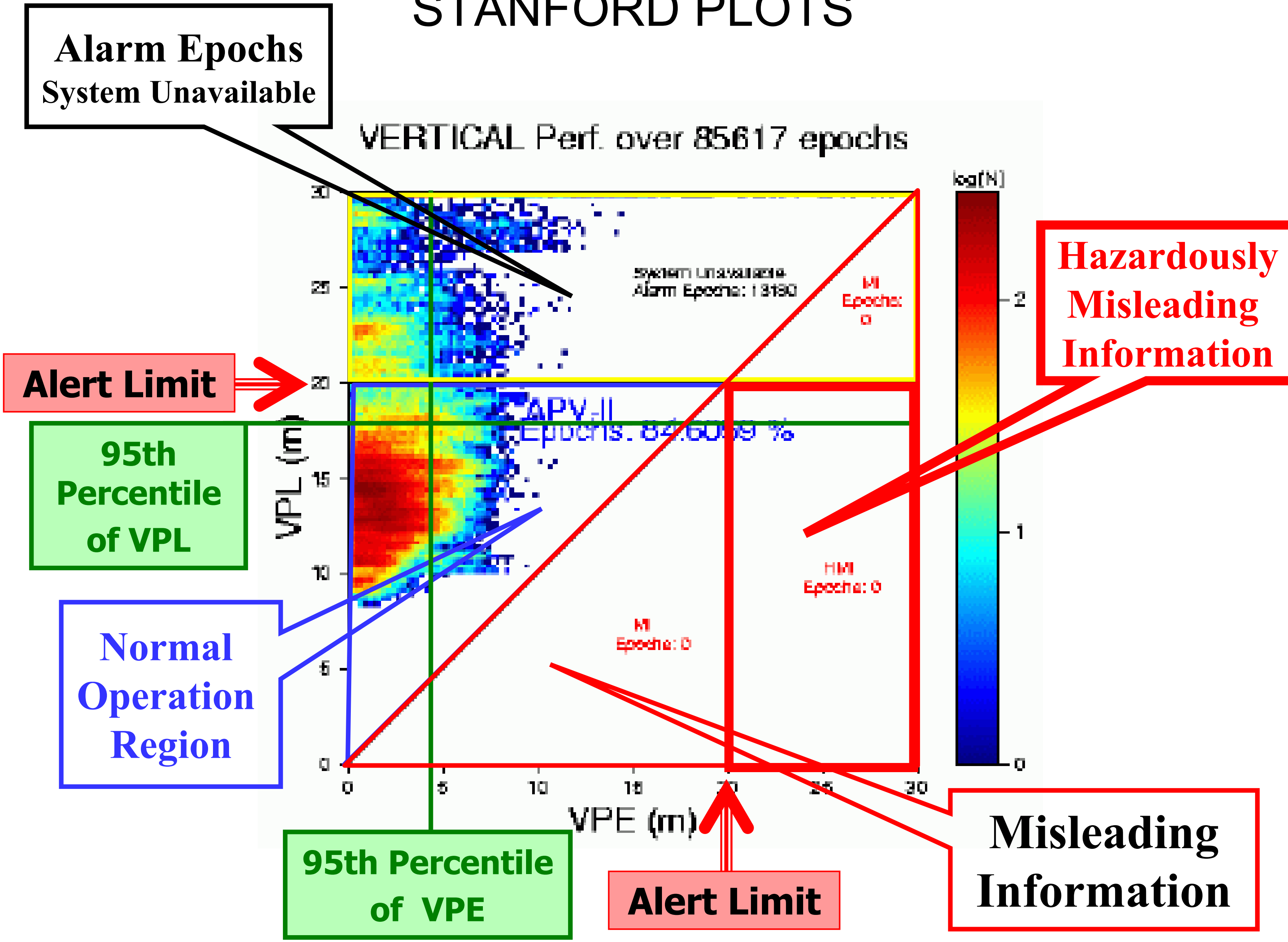
$$X \sim N(0,1)$$
$$p(|X| > K_v) = 10^{-7} \Rightarrow K_v = 5.33$$
$$p(|X| > K_h) = 10^{-9} \Rightarrow K_h = 6.0$$

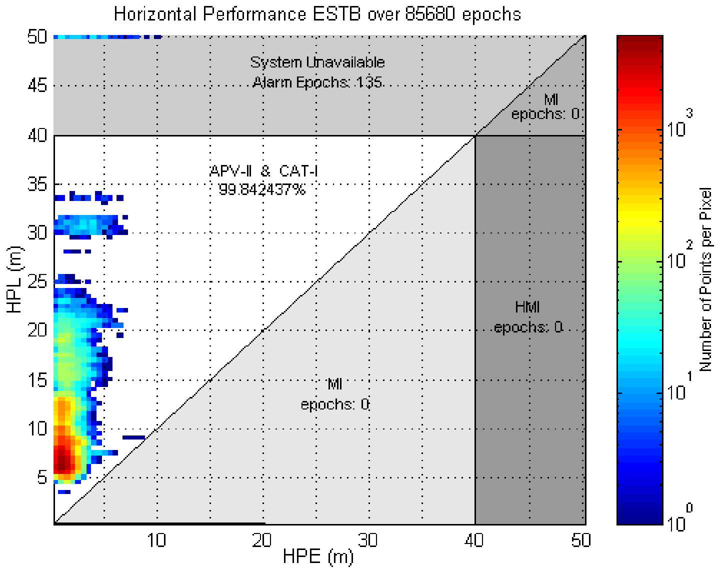
$$Y \sim Rayleigh$$
$$p(|Y| > K_h) = 5 \cdot 10^{-9} \Rightarrow K_h = 6.18$$

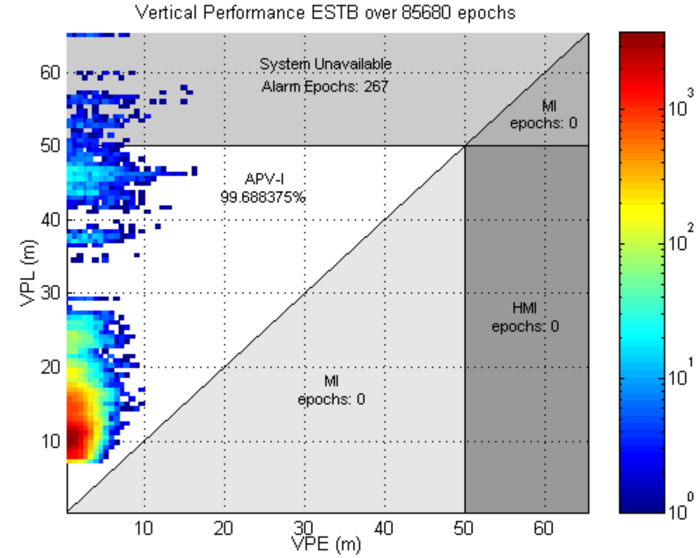


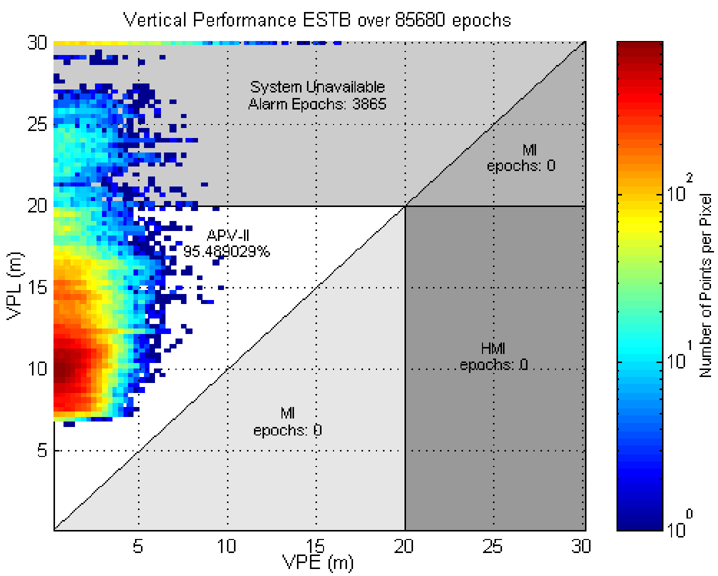
- Each epoch, HPL/VPL are compared with the Alert Limits (HAL/VAL) defined for the operation mode:
  - Hazardously Misleading Information (HMI): NSE> HAL or VAL
    ➔ INTEGRITY RISK
  - Misleading Information (MI): NSE > HPL or VPL
    ➔Out-Of-Tolerence cond.
- The system is set unavailable when XPL > XAL

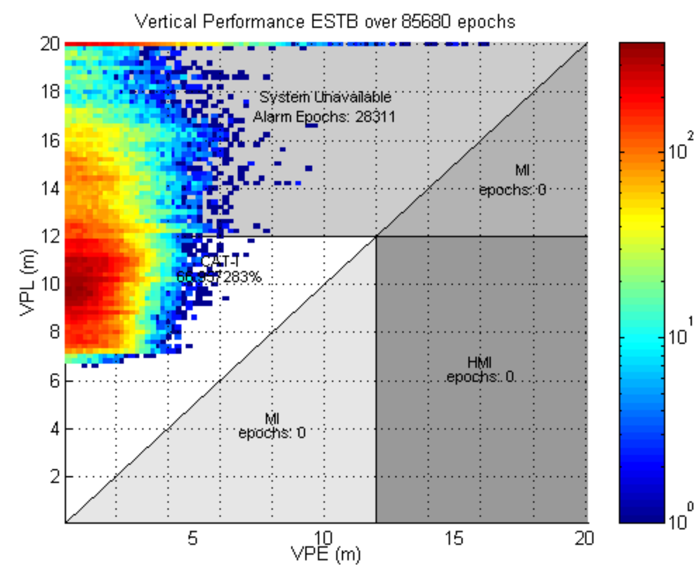
STANFORD PLOTS




Horizontal Performance ESTB over 85680 epochs
System Unavailable
Alarm Epochs: 135
MI
epochs: 0
APV-II & CAT-I
99.842437%
HMI
epochs: 0
MI
epochs: 0
HPL (m)
HPE (m)
Number of Points per Pixel

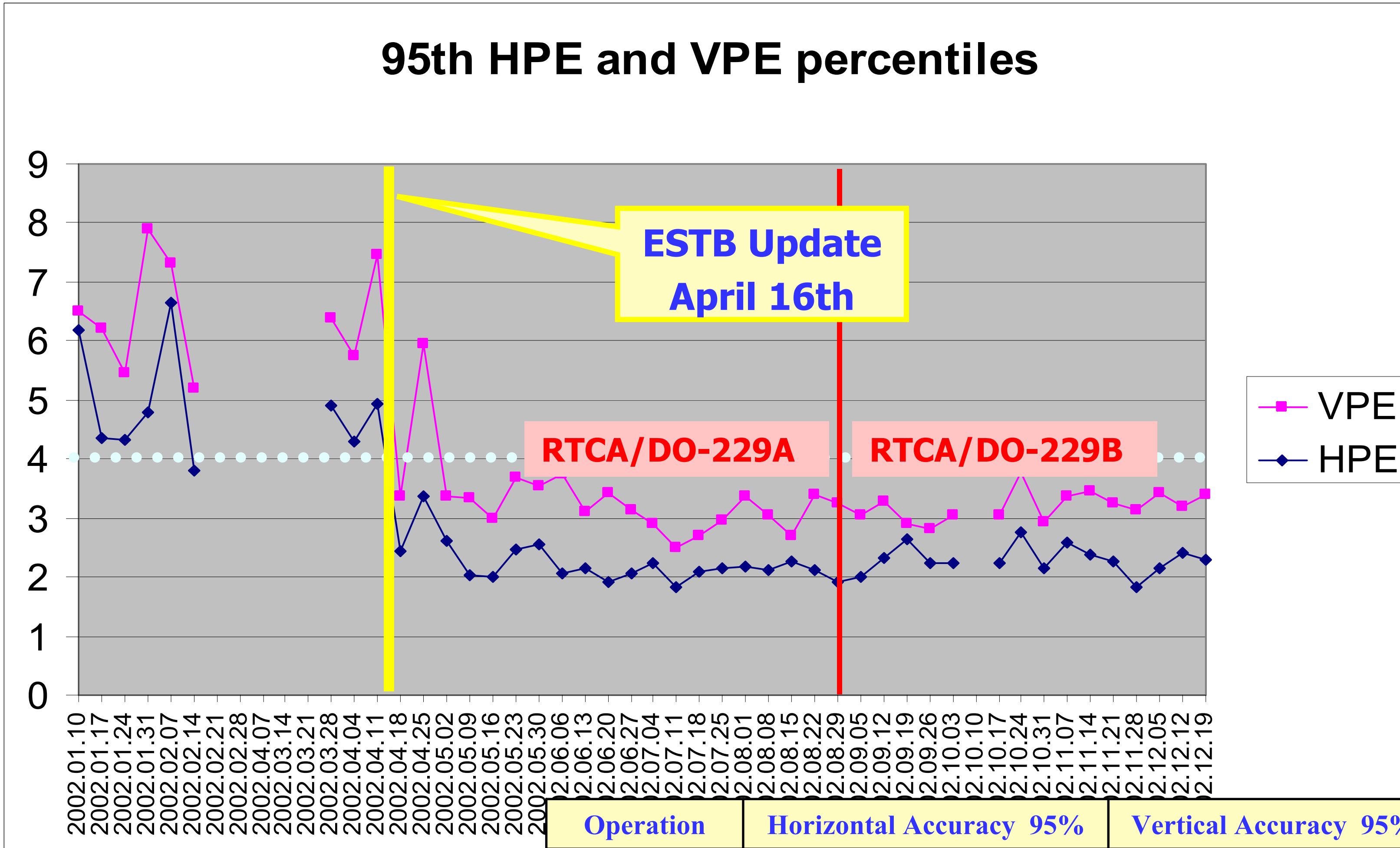

Vertical Performance ESTB over 85680 epochs
System Unavailable
Alarm Epochs: 267
MI
epochs: 0
APV-I
99.688375%
HMI
epochs: 0
MI
epochs: 0
VPL (m)
VPE (m)
Number of Points per Pixel


Vertical Performance ESTB over 85680 epochs
System Unavailable
Alarm Epochs: 3865
MI
epochs: 0
APV-II
95.489029%
HMI
epochs: 0
MI
epochs: 0
VPL (m)
VPE (m)
Number of Points per Pixel


Vertical Performance ESTB over 85680 epochs
System Unavailable
Alarm Epochs: 28311
MI
epochs: 0
CAT-I
HMI
epochs: 0
MI
epochs: 0
VPL (m)
VPE (m)
Number of Points per Pixel

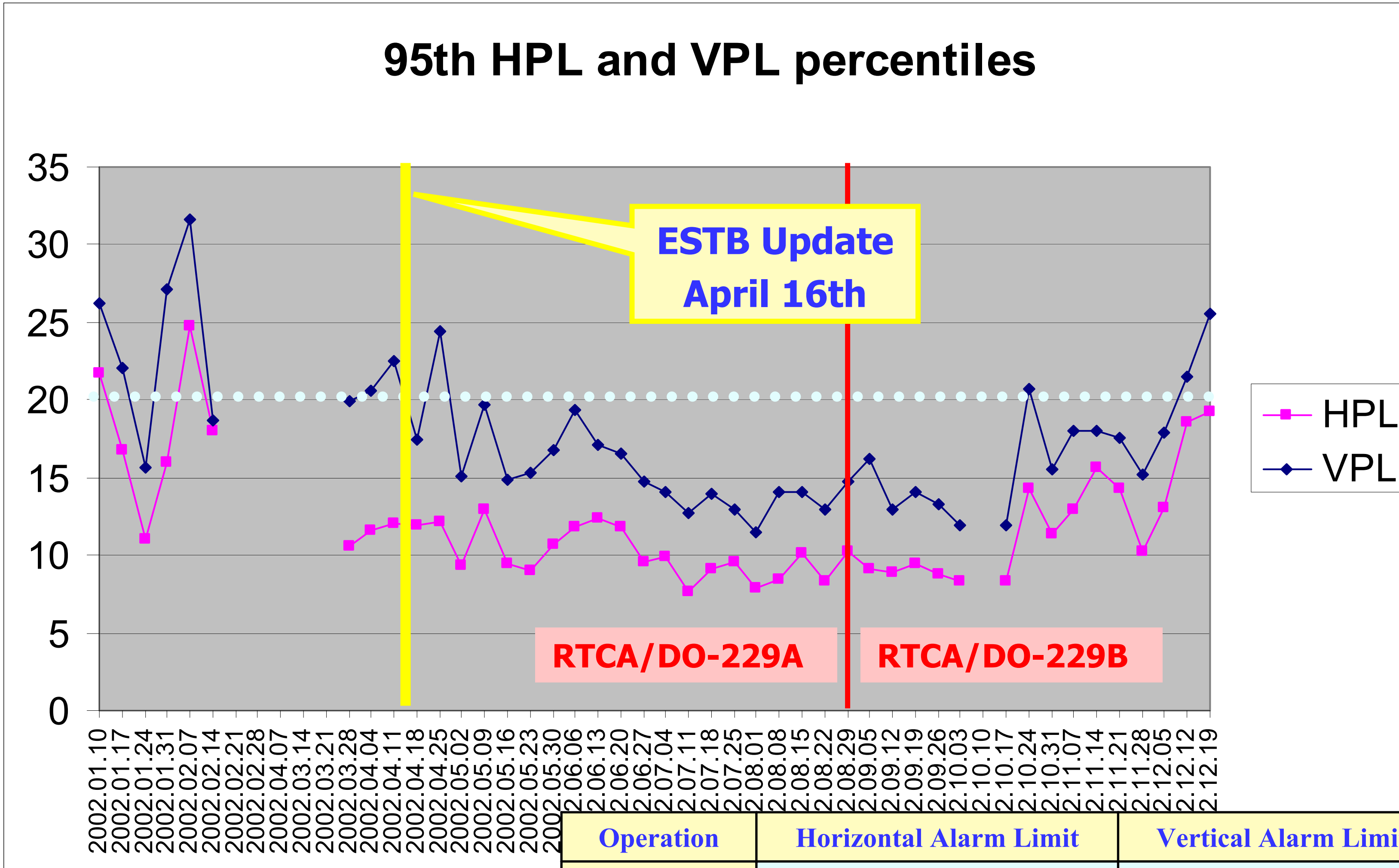
ESTB Performances in Barcelona during 2002

- The ESTB is a full-scale real-time prototype of the EGNOS system, but it is reduced in size and capabilities.
- Therefore it has to be noted that the results obtained with ESTB will not be the same as the final EGNOS performances.
- EGNOS will benefit from a better infrastructure and a more developed and robust design.



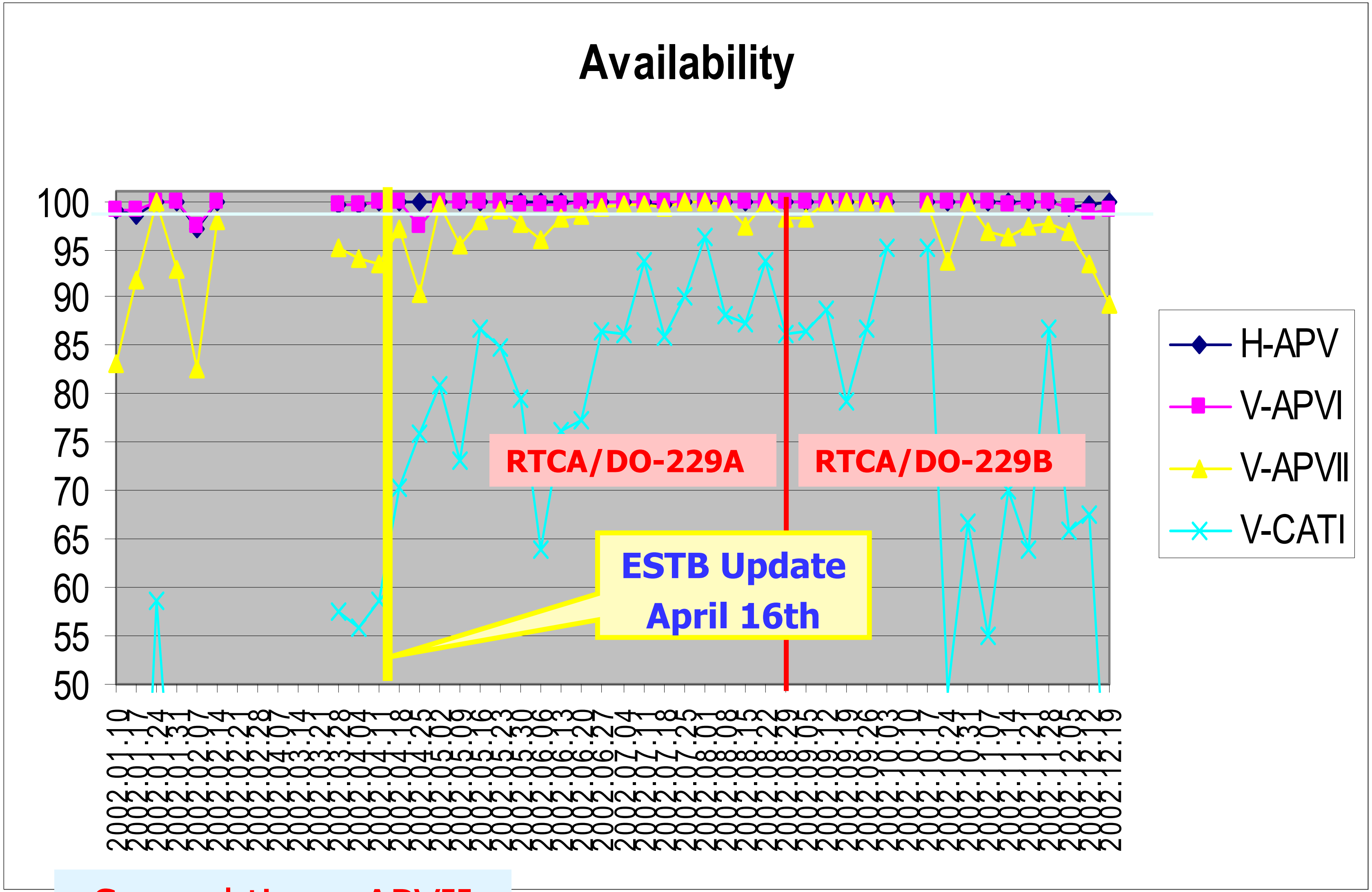
VPE 95th Percentile typically lower than 4 m

Operation	Horizontal Accuracy 95%	Vertical Accuracy 95%
NPA	220 m	N/A
APV-I	220 m	20 m
APV-II	16 m	8 m
CAT-I	16 m	6-4 m

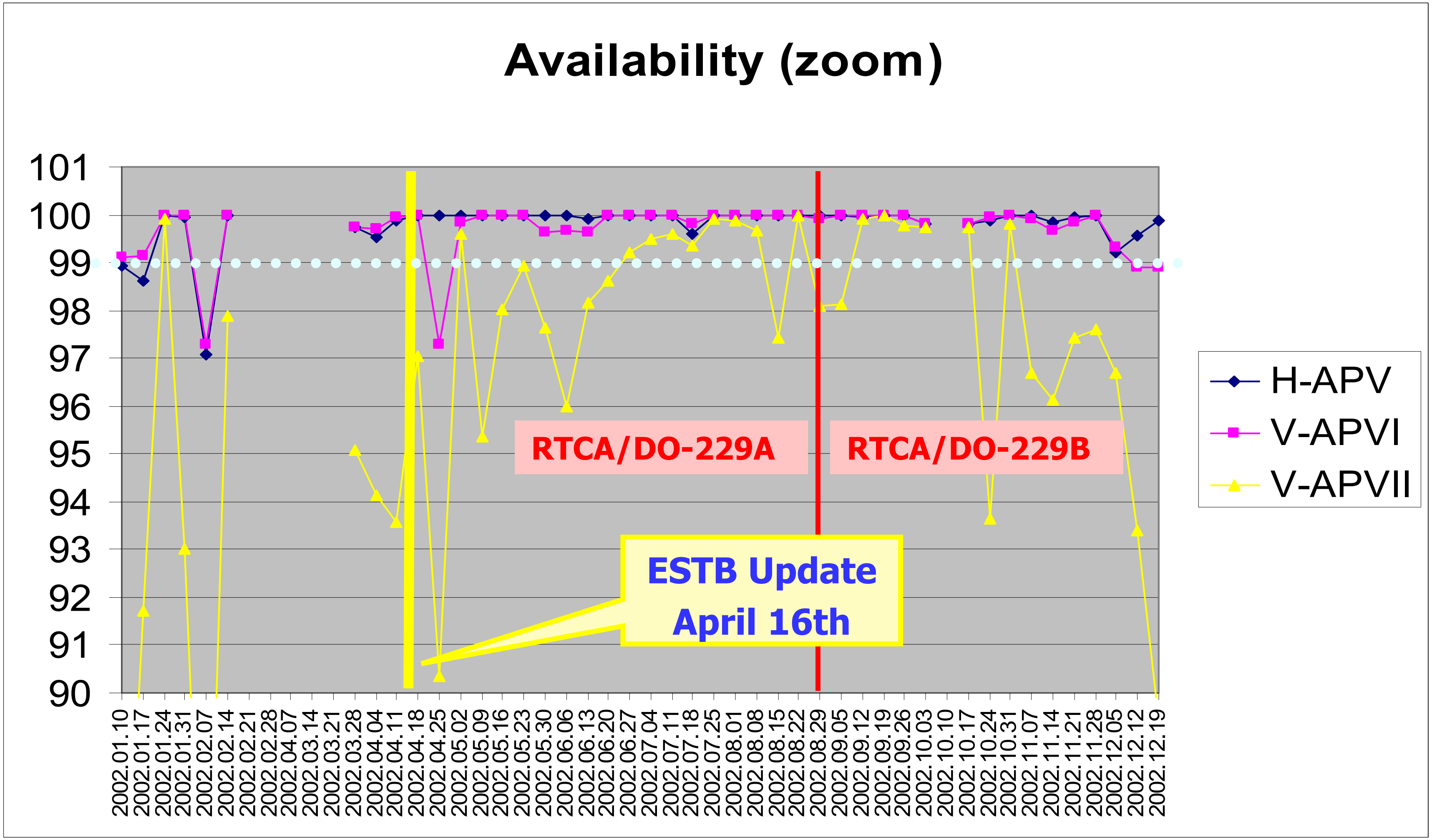


VPL 95th Percentile typically lower than 20 m

Operation	Horizontal Alarm Limit	Vertical Alarm Limit
NPA	556 m	N/A
APV-I	556 m	50 m
APV-II	40 m	20 m
CAT-I	40 m	12 m



Several times APVII availability > 99%

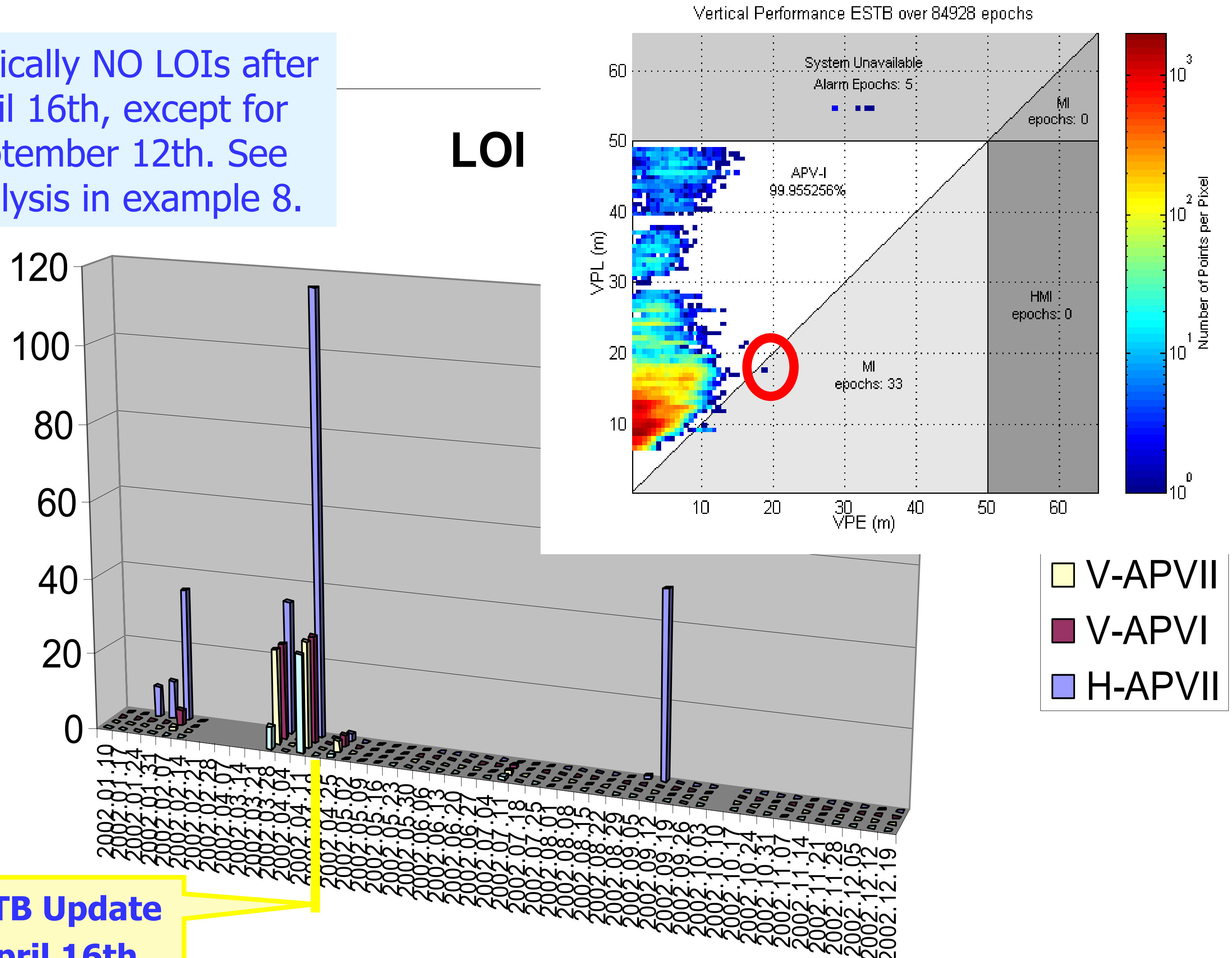


Several times APVII
availability > 99%

Manuel Hernández-Pajares, J. Miguel Juan, Jaume Sanz, Xavier Prats, February 2002.

Basically NO LOIs after April 16th, except for September 12th. See analysis in example 8.

LOI

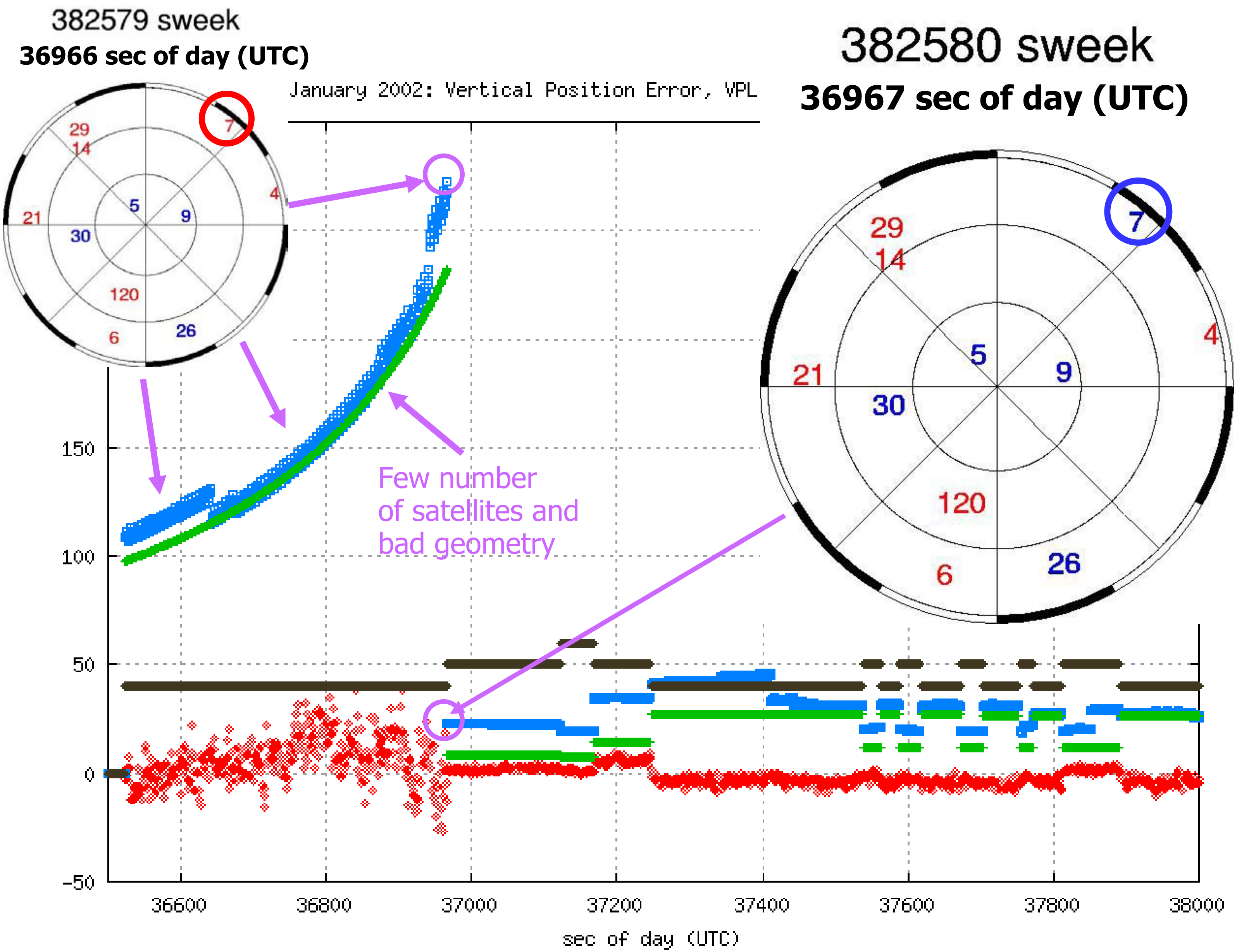


ESTB Update
April 16th

EXAMPLE 3 :

Large Protection Level Values (ESTB January 10th 2002)

4 satellites used in the computations



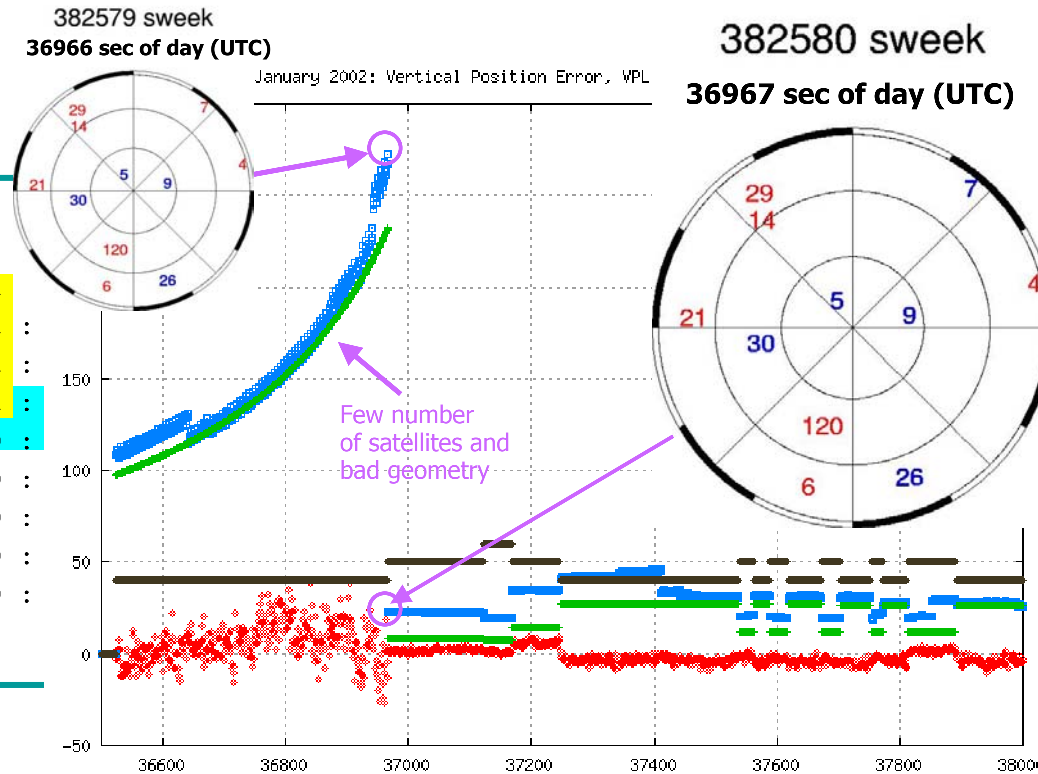
Manuel Hernández-Pajares, J. Miguel Juan, Jaume Sanz, Xavier Prats, February 2002.

Which satellites are being used?

N. Sat. used

382576	11	4	:	30	5	:	21	-	:	7	11			
382577	11	4	:	30	5	:	21	-	:	7	11	:		
382578	11	4	:	30	5	:	21	-	:	7	11	:		
382579	11	4	:	30	5	:	21	-	:	7	11	:		
382580	11	5	:	30	5	:	21	-	:	7	10	:		
382581	11	5	:	30	5	:	21	-	:	7	10	:		
382582	11	5	:	30	5	:	21	-	:	7	10	:		
382583	11	5	:	30	5	:	21	-	:	7	10	:		
382584	11	5	:	30	5	:	21	-	:	7	10	:		

N. Sat. in view



No ephemeris

Used for nav.

No differential Corr.

UDRE>10

The MOPS (RTCA Do 229A) 2.1.1.5.2, establish the satellites deselecting for:

-UDRE=14 (not monitored)

and

-UDRE=15 (don't use)

2.1.4.7.1: In addition, for Precision Approach:
UDRE< 11.

EXAMPLE 4 :

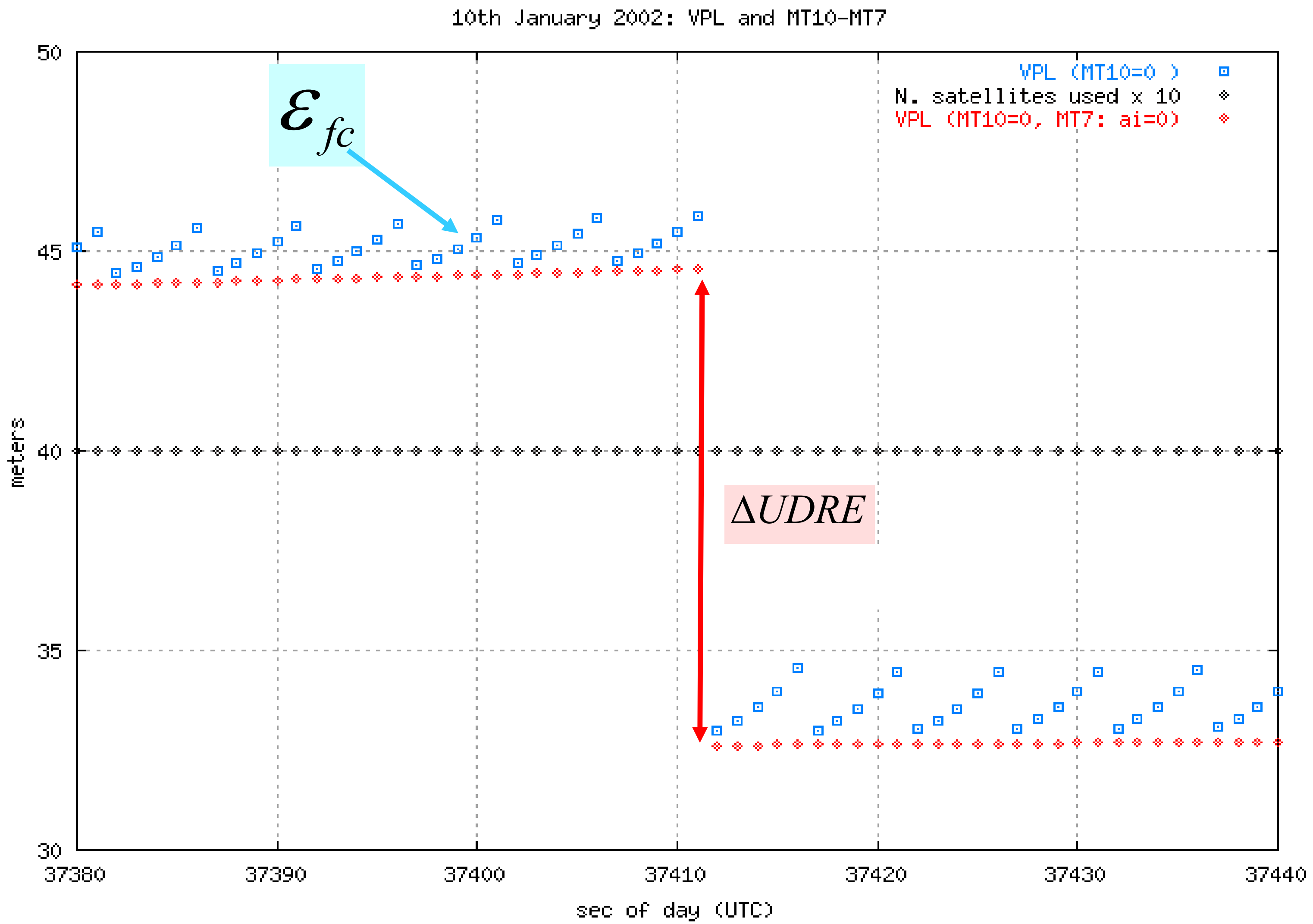
Fast Correction degradation (ESTB January 10th 2002)

4 or 5 satellites used in the computations

$$\varepsilon_{fc} = a\frac{(t-t_u+t_{lat})^2}{2}$$

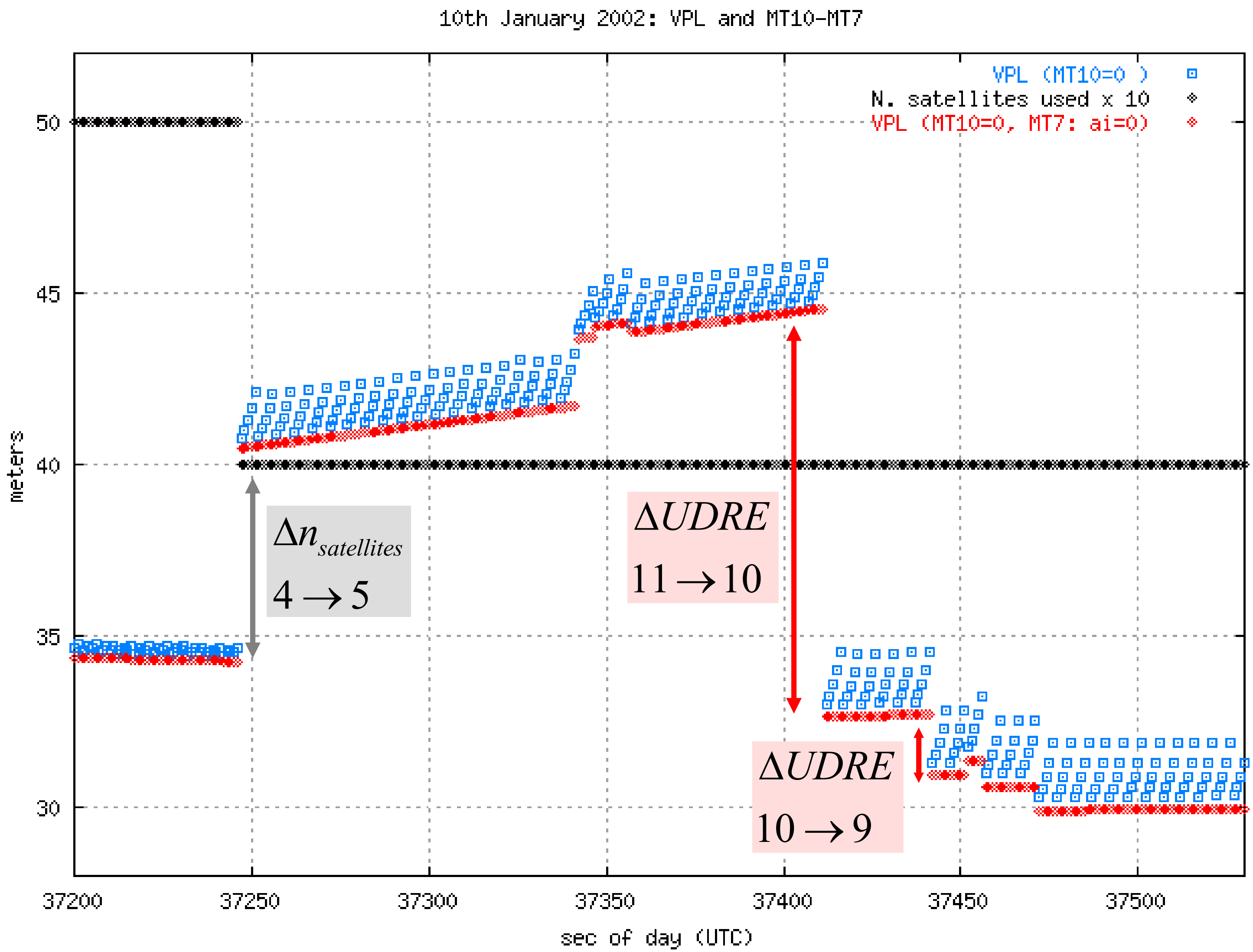
$$a = 5.8 mm/s^2 \quad ; \quad t_{lat} = 7s$$

$$t - t_u = t - t_{fc} \leq 5\,s\,(tipically)$$



Manuel Hernández-Pajares, J. Miguel Juan, Jaume Sanz, Xavier Prats, February 2002.

$$\sigma^2{}_{i,flt} = \sigma^2{}_{UDRE} + \varepsilon^2{}_{fc} + \varepsilon^2{}_{rrc} + \varepsilon^2{}_{ltc} + \varepsilon^2{}_{er}$$



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EXAMPLE 5 :

Periods without Nav. Sol. (ESTB, February 14th 2002)

Analysis of Feb 14th

21 sec
12 sec

Sec of Week	Message Type	PRN of Satellites in use					
413846	MT02	11	14	20	28	29	31
413847	MT03	11	14	20	28	29	31
413848	MT04	11	14	20	28	29	31
413849	MT25	11	14	20	28	29	31
413850	MT00	11	14	20	28	29	31
413851	MT26 BN4 BI1	11	14	20	28	29	31
413852	MT26 BN4 BI1	11	14	20	28	29	31
413853	MT26 BN4 BI1	11	14	20	28	29	31
413854	MT26 BN4 BI1	11	14	20	28	29	31
413855	MT26 BN4 BI2	11	14	20	28	29	31
413856	MT26 BN4 BI2	11	14	20	28	29	31
413857	MT26 BN4 BI2	11	14	20	28	29	31
413858	MT26 BN4 BI2	11	14	20	28	29	31
413859	MT26 BN4 BI3			20	28	29	31
413860	MT26 BN4 BI3						31
413861	MT26 BN4 BI3						
413862	MT26 BN4 BI3						
413863	MT26 BN4 BI4						
413864	MT26 BN4 BI4						
413865	MT26 BN4 BI4						
413866	MT26 BN4 BI1						
413867	MT02						
413868	MT03	11	14				
413869	MT04	11	14	20	28	29	
413870	MT00	11	14	20	28	29	31

SIS anomaly that should be solved with MT6 broad.

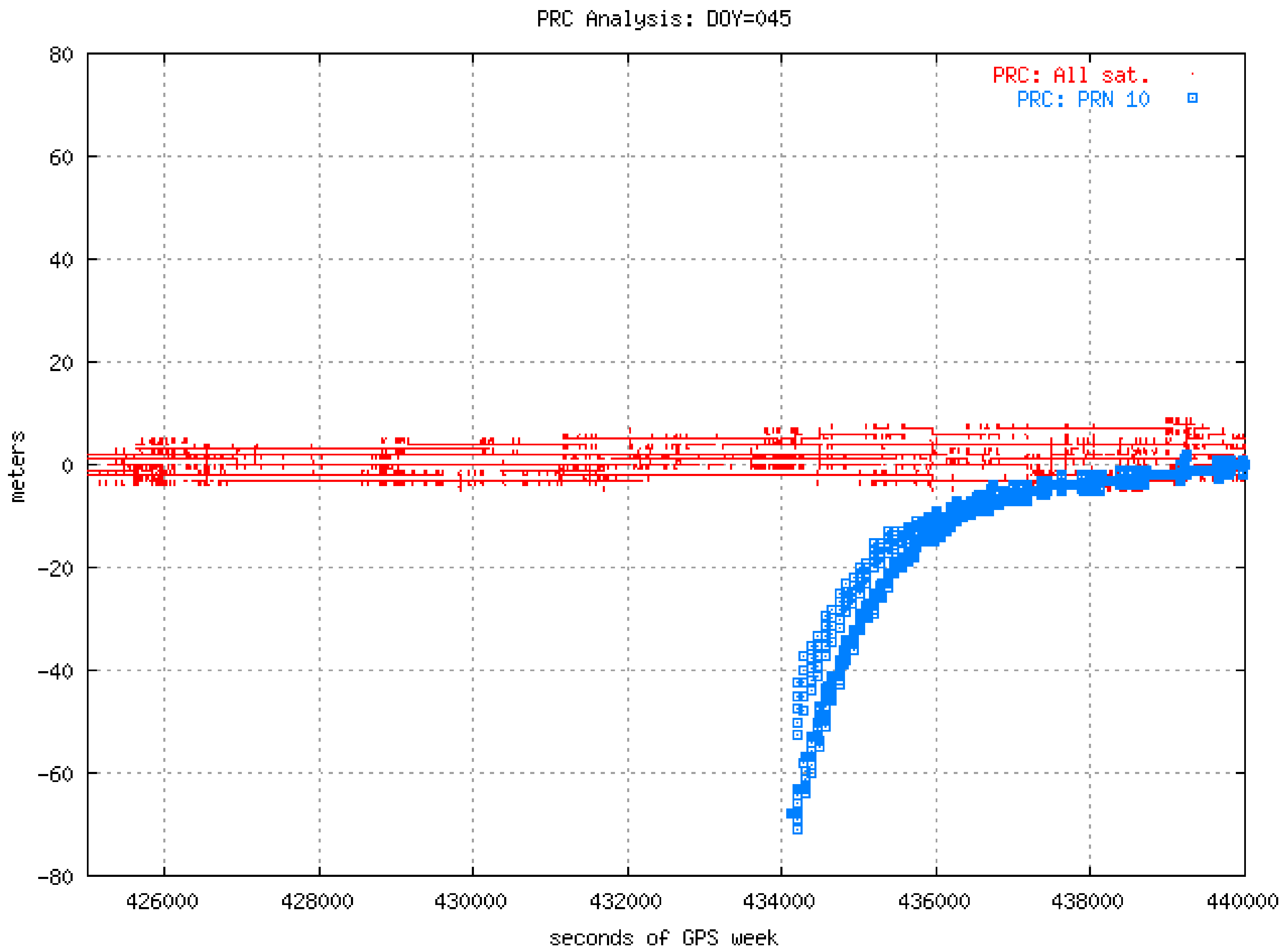
- MT26 repetitions (alarm condition).
- FC updated after 21 seconds.

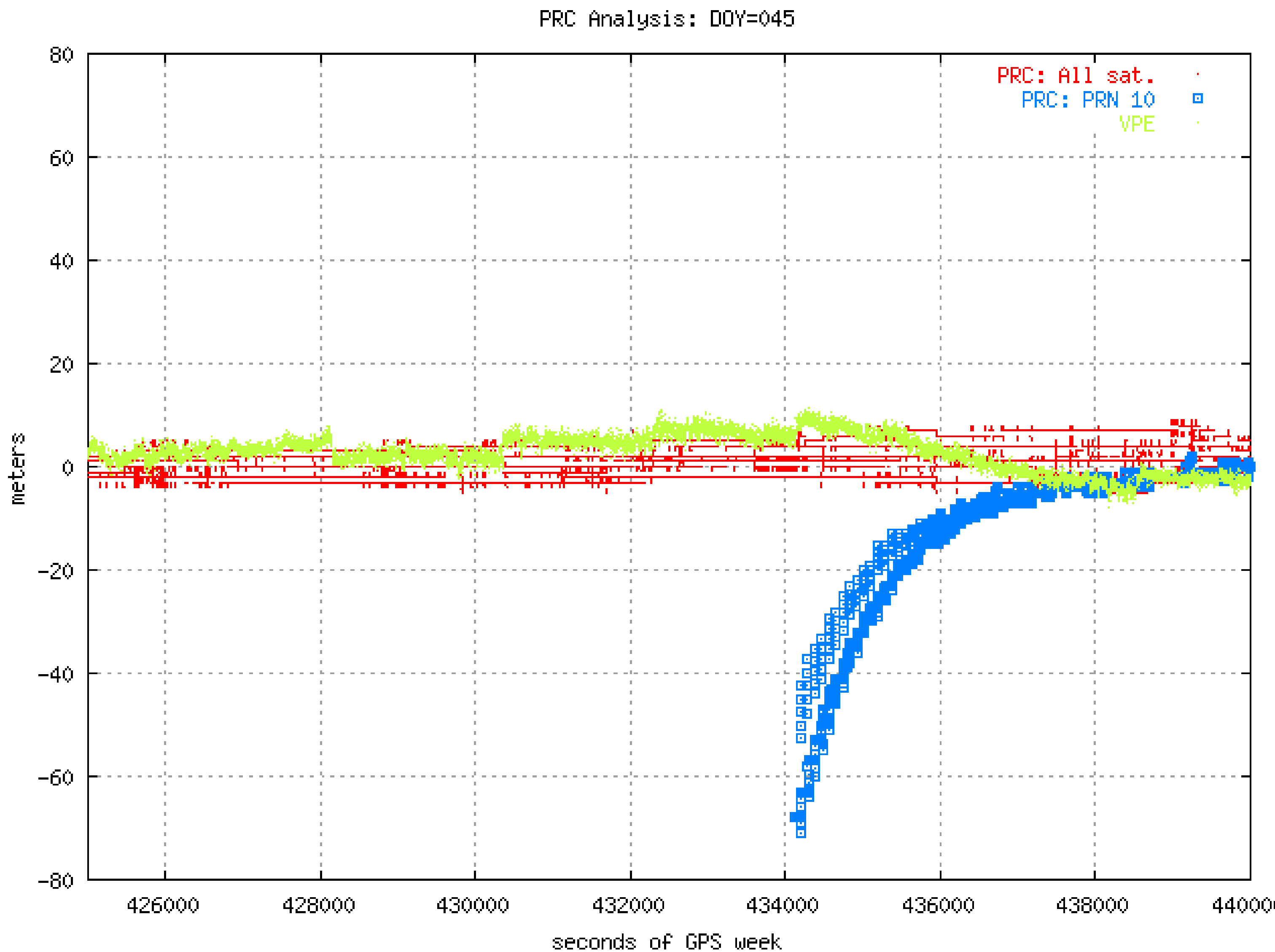
The satellites are deselected after **12sec,** due to the UDRE Time-Out.

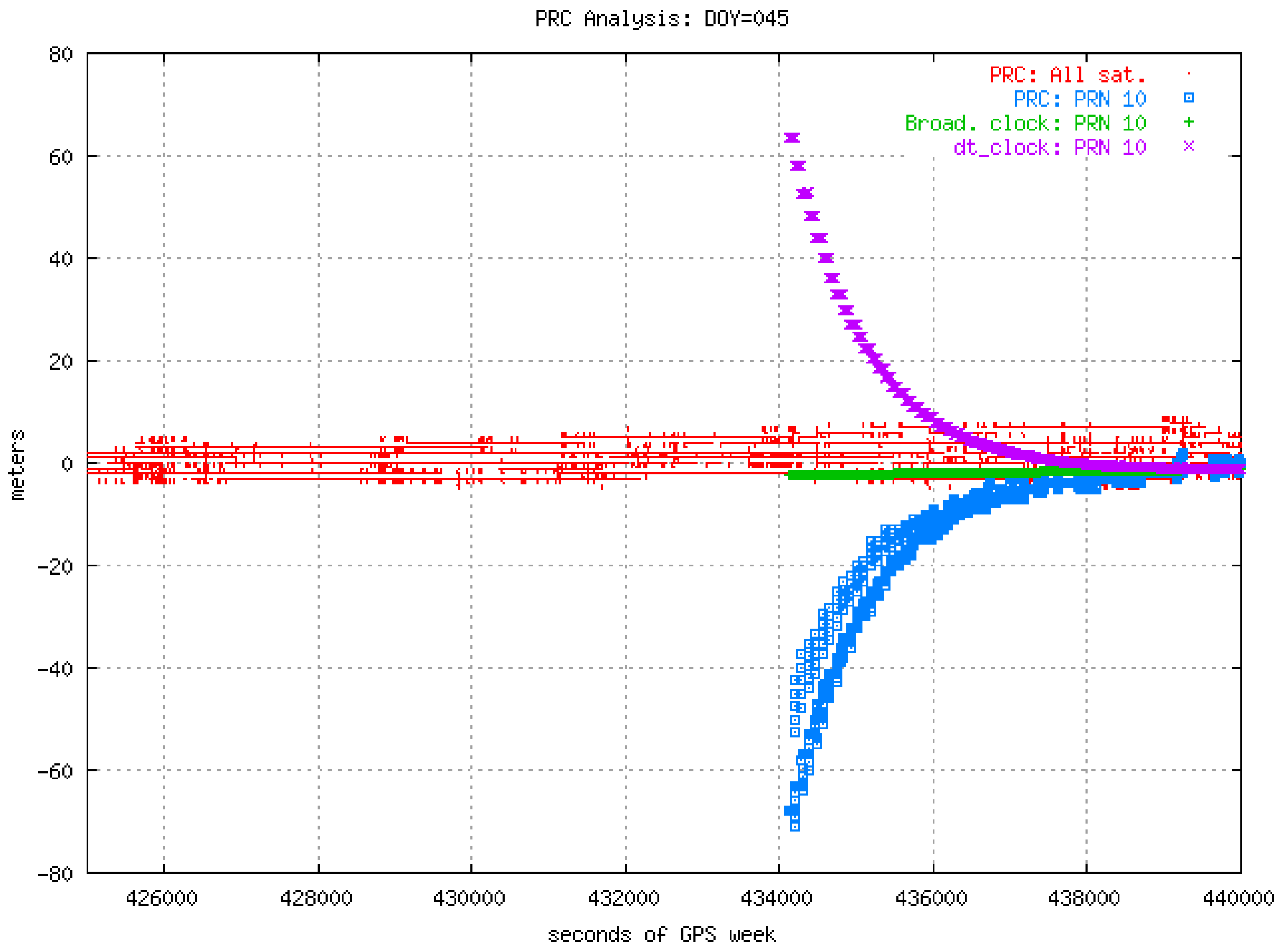
M3-SYSTEMS
ENAC

EXAMPLE 6 :

Analysis of PRC (PRN10) Large Values (ESTB February 14th 2002)


PRC Analysis: DOY=045
PRC: All sat.
PRC: PRN 10
meters
80
60
40
20
0
-20
-40
-60
-80
426000
428000
430000
432000
434000
436000
438000
440000
seconds of GPS week


PRC Analysis: DOY=045
PRC: All sat.
PRC: PRN 10
VPE
meters
80
60
40
20
0
-20
-40
-60
-80
426000
428000
430000
432000
434000
436000
438000
440000
seconds of GPS week

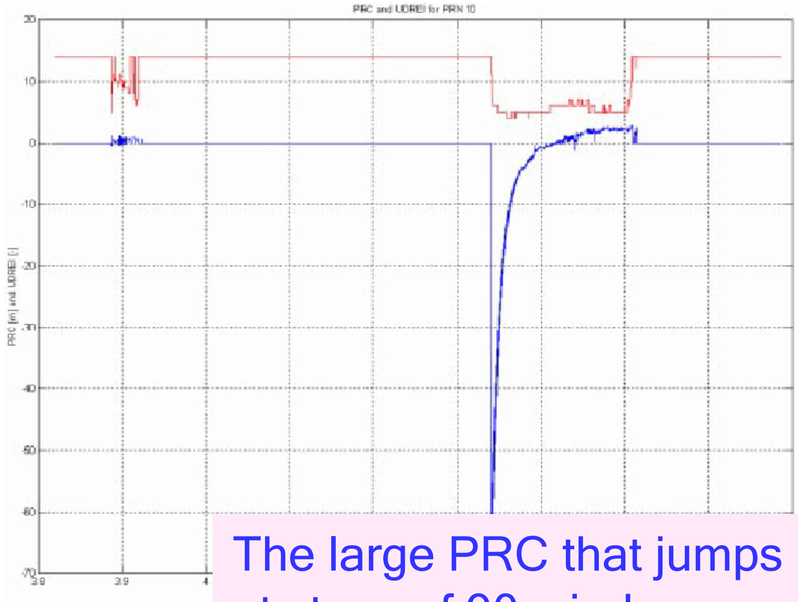

PRC Analysis: DOY=045
PRC: All sat.
PRC: PRN 10
Broad. clock: PRN 10
dt_clock: PRN 10
meters
80
60
40
20
0
-20
-40
-60
-80
426000
428000
430000
432000
434000
436000
438000
440000
seconds of GPS week

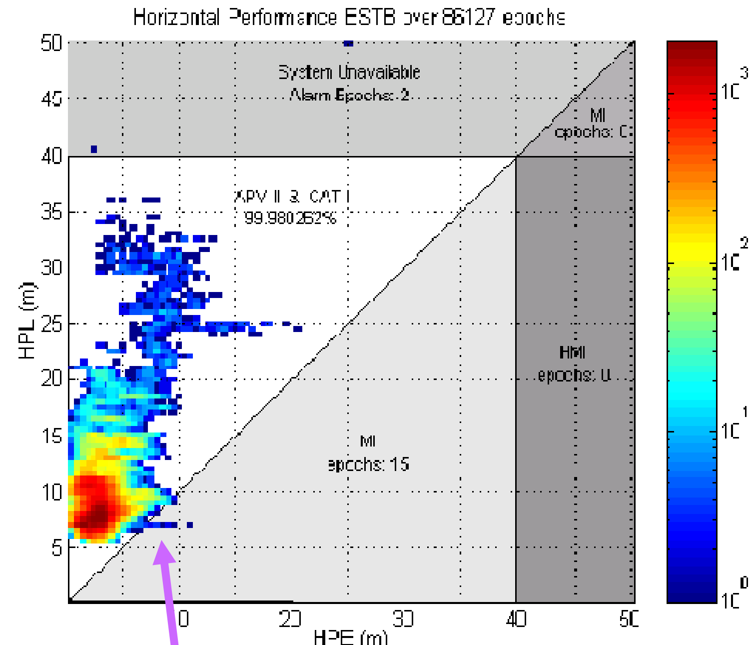
EXAMPLE 7 :

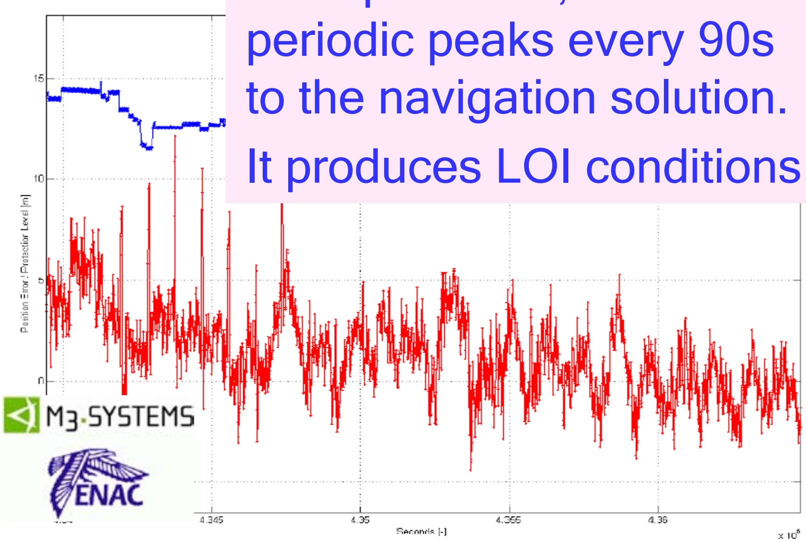
LOI when High PRC for PRN10

(ESTB February 14th 2002)

Analysis of Feb 14th 2002: **LOI when High PRC for PRN10**

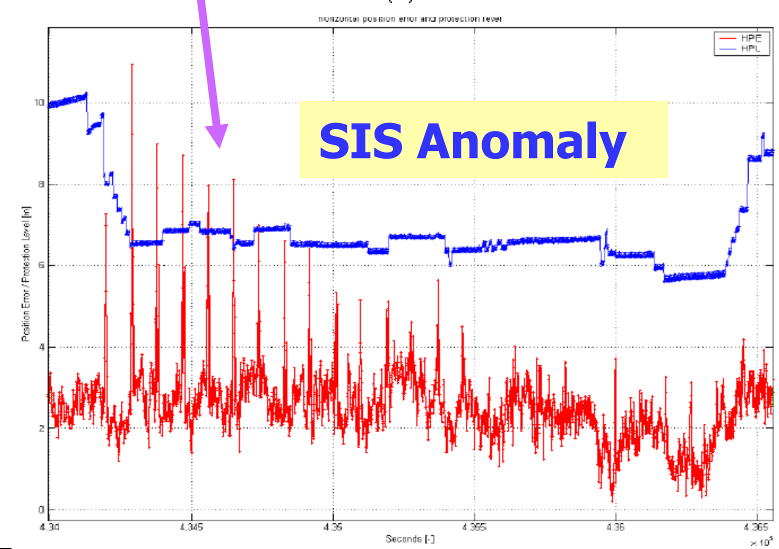






The large PRC that jumps at steps of 90s, induces periodic peaks every 90s to the navigation solution.

It produces LOI conditions.



SIS Anomaly

M3-SYSTEMS

ENAC

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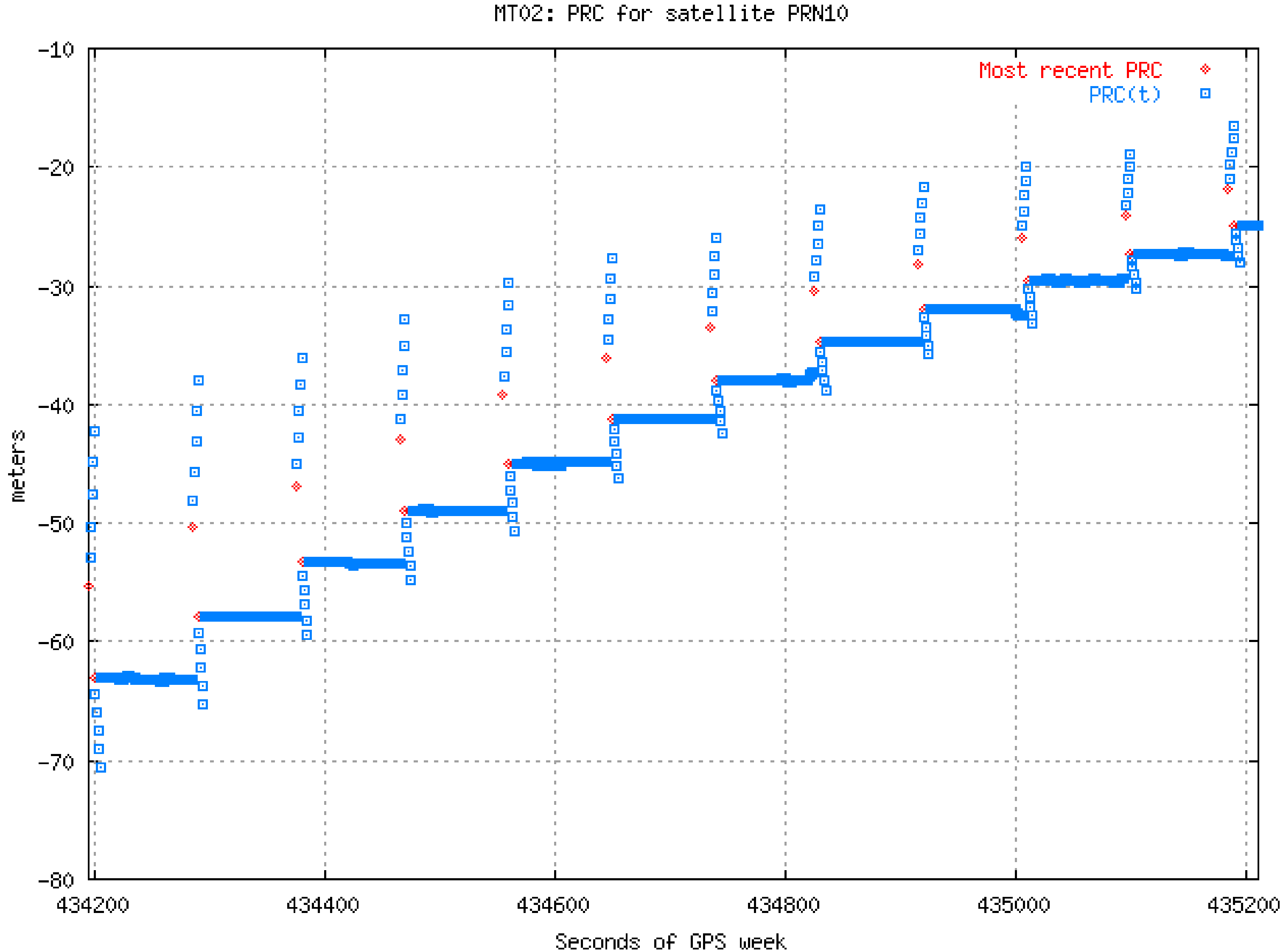
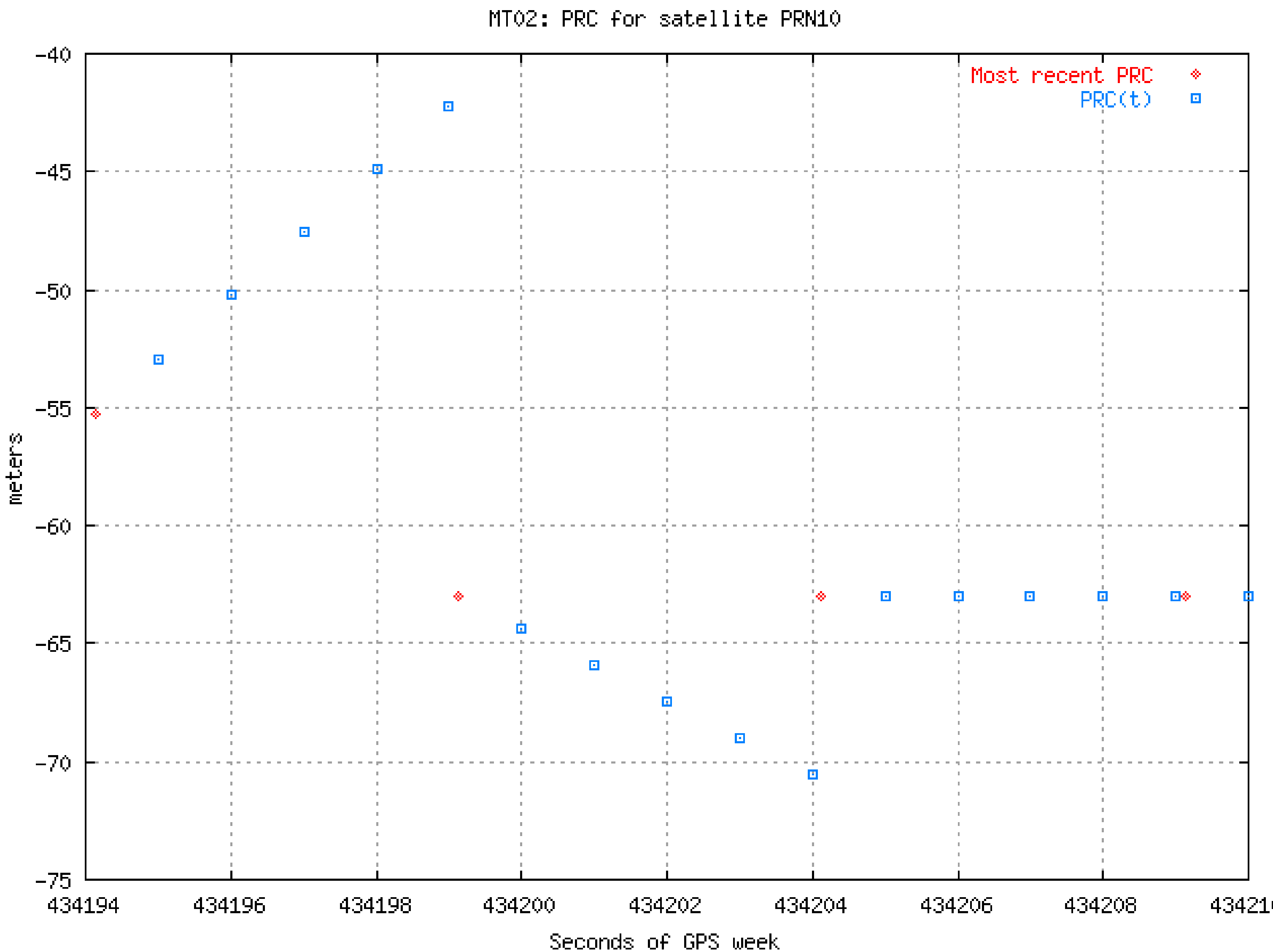

MT02: PRC for satellite PRN10
Most recent PRC
PRC(t)
meters
-10
-20
-30
-40
-50
-60
-70
-80
434200
434400
434600
434800
435000
435200
Seconds of GPS week


MT02: PRC for satellite PRN10
Most recent PRC
PRC(t)
meters
-40
-45
-50
-55
-60
-65
-70
-75
434194
434196
434198
434200
434202
434204
434206
434208
434210
Seconds of GPS week

UPC

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EXAMPLE 8 :

LOIs due to wrong ionospheric corrections

(ESTB September 12th 2002)

UPC1 and UPC2 16Km baseline

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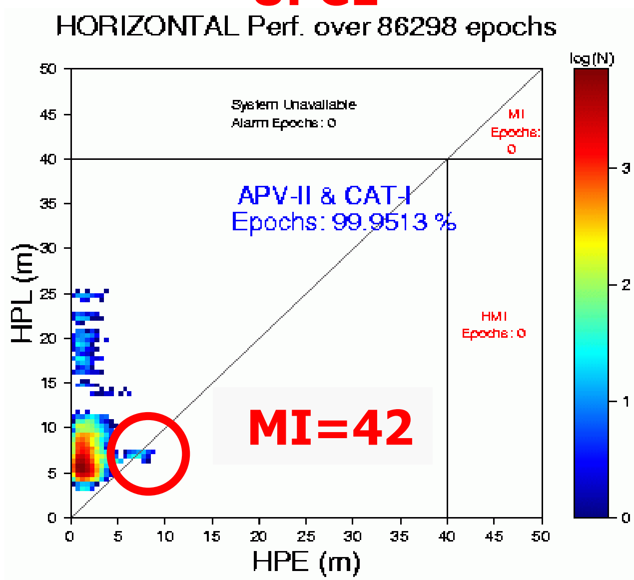
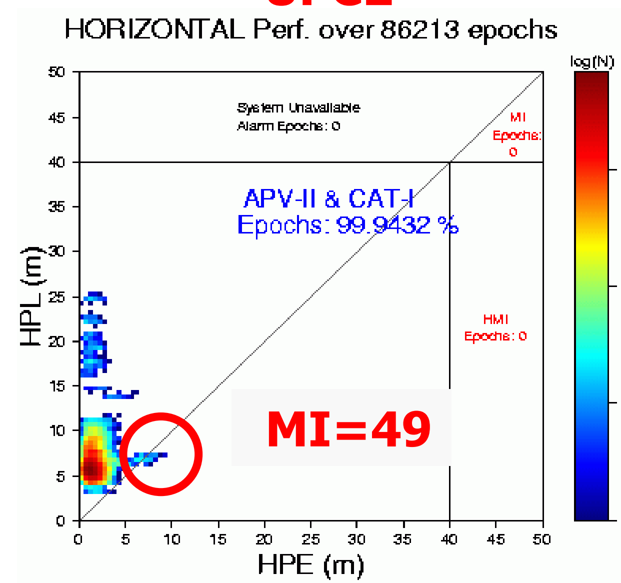
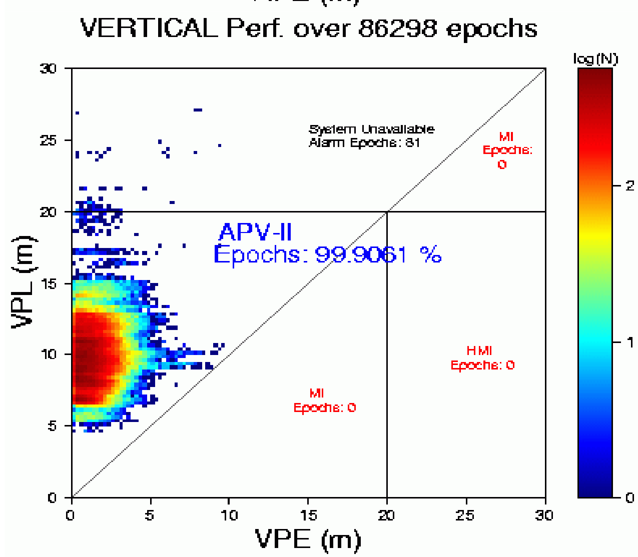
UPC1 | UPC2

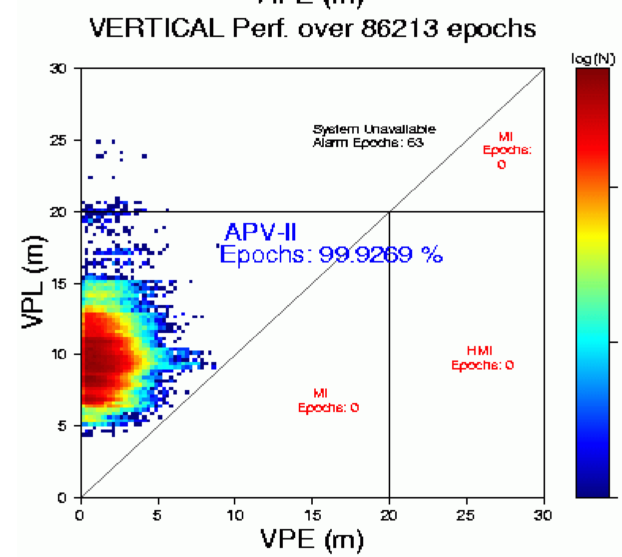
HOR



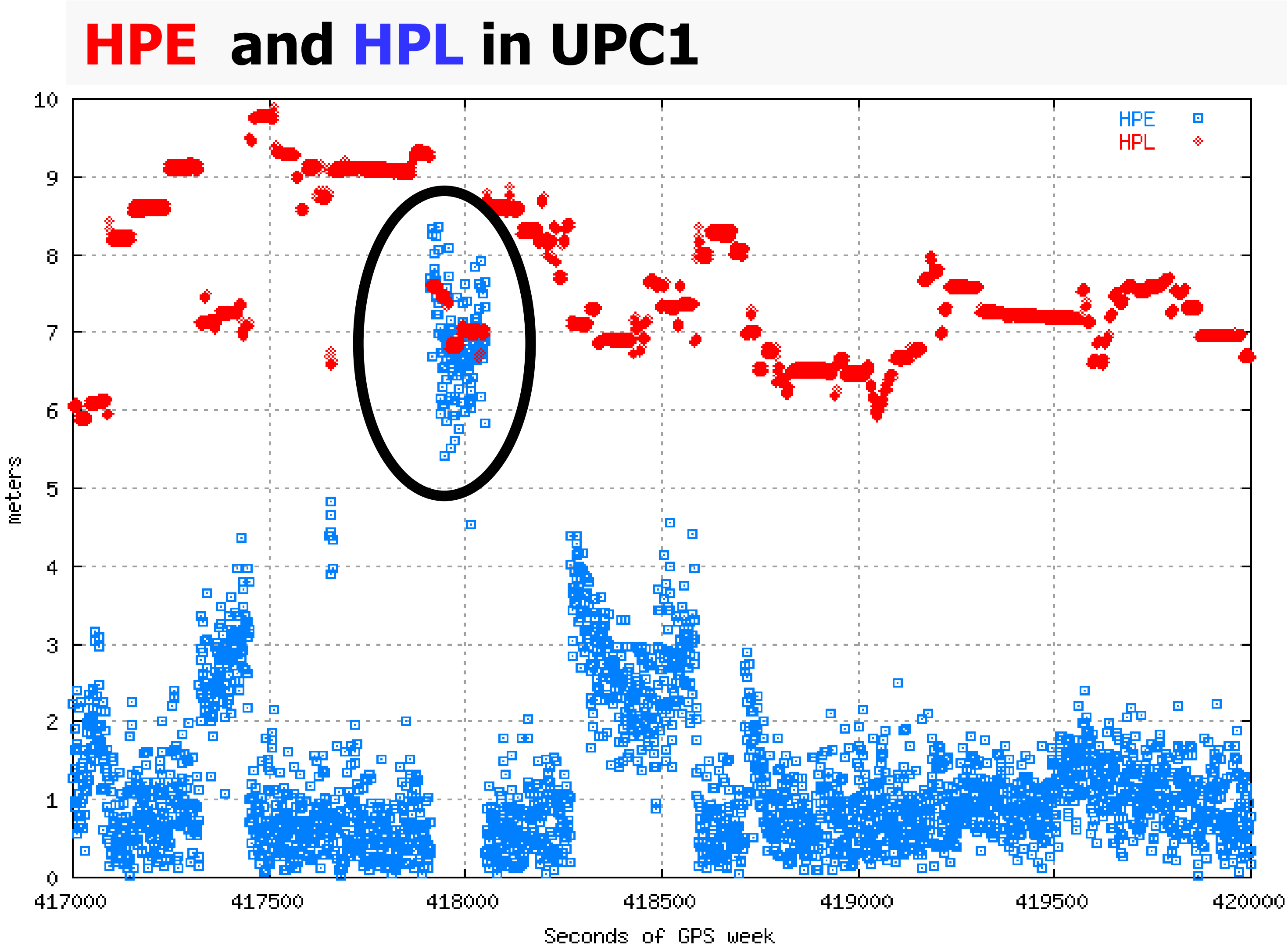


VERT





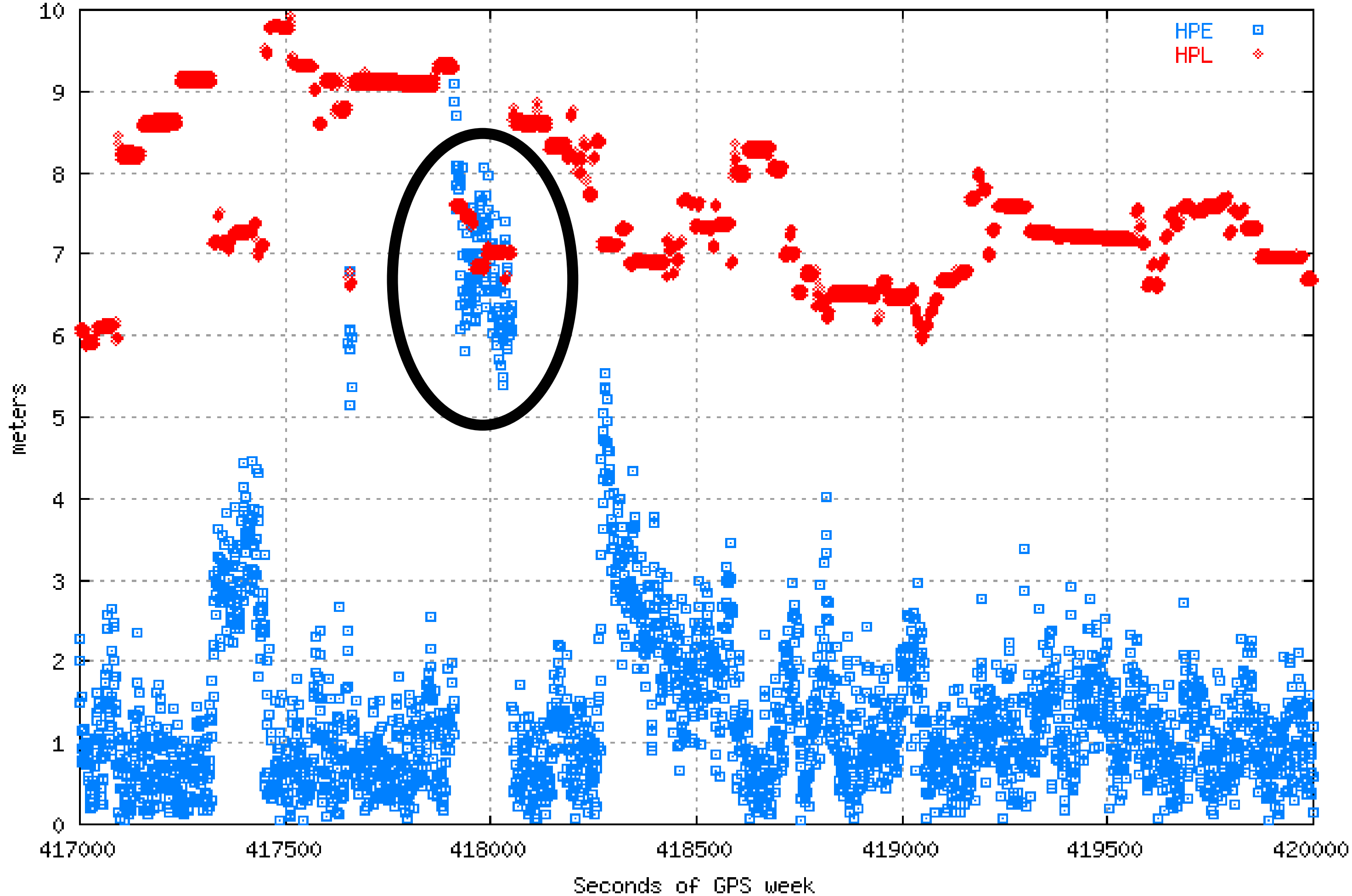
Sep 12th 2002 MI analysis



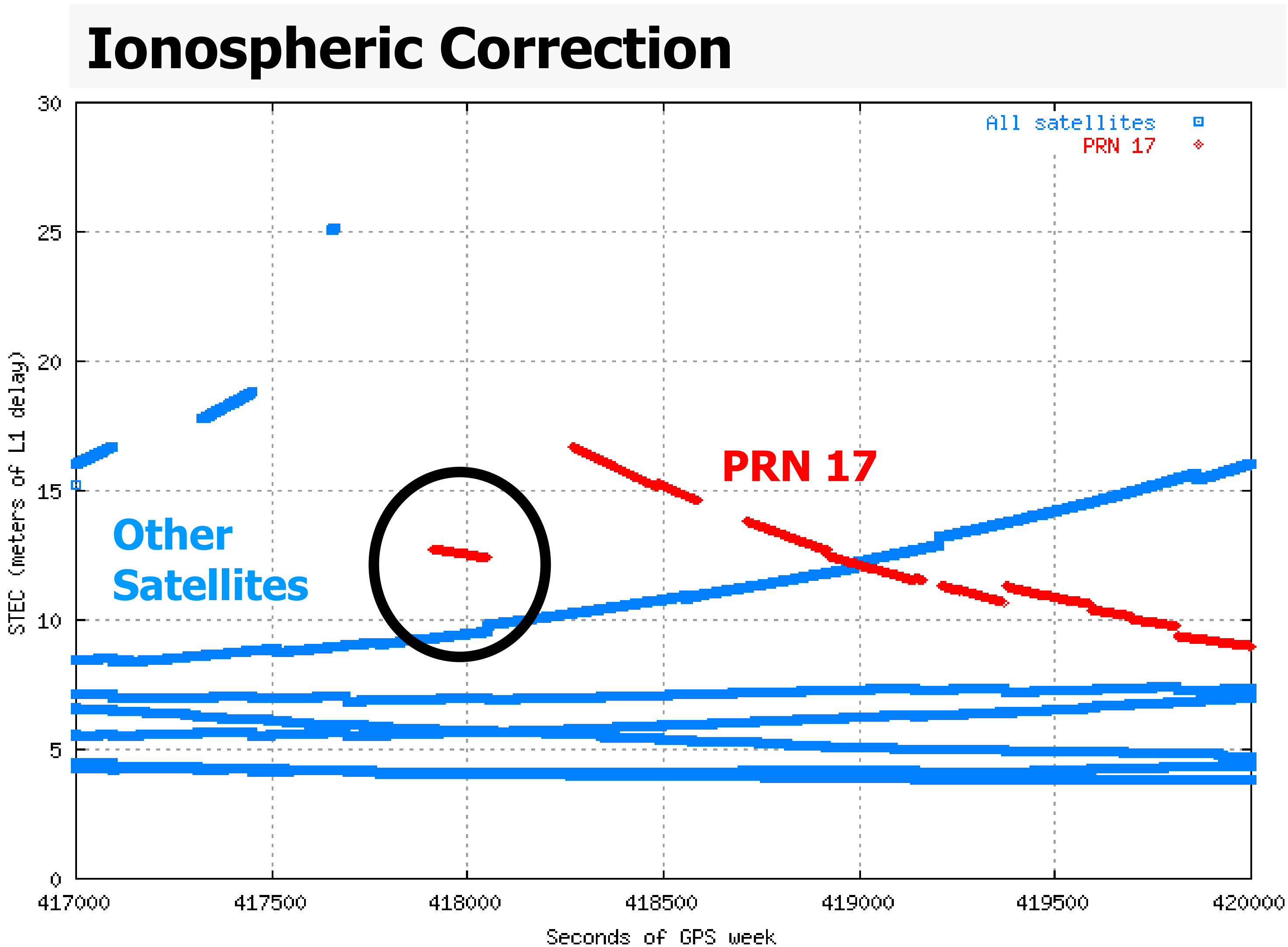
Manuel Hernández-Pajares, J. Miguel Juan, Jaume Sanz, Xavier Prats, February 2002.

Sep 12th 2002 MI analysis

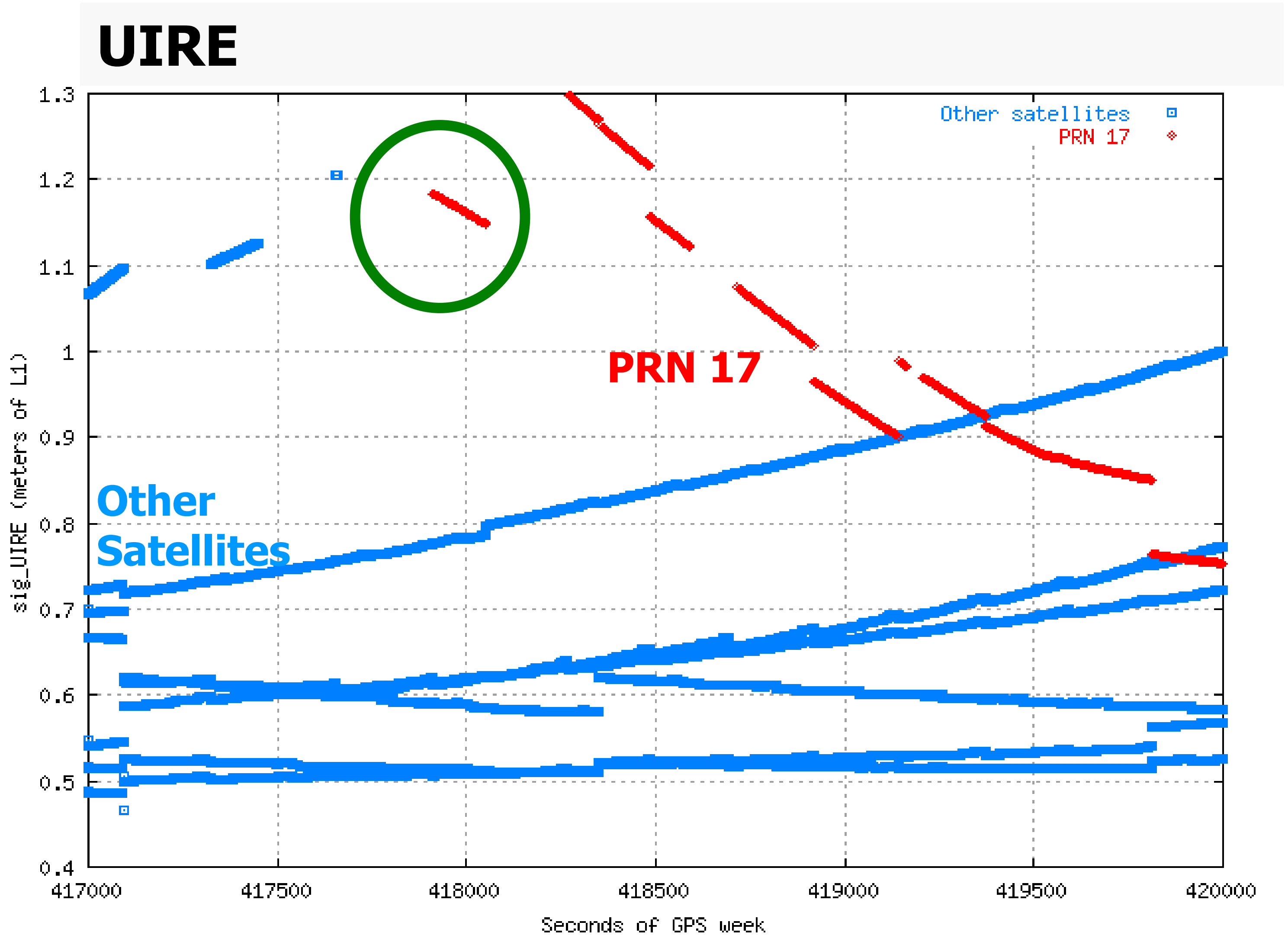
HPE and HPL in UPC2



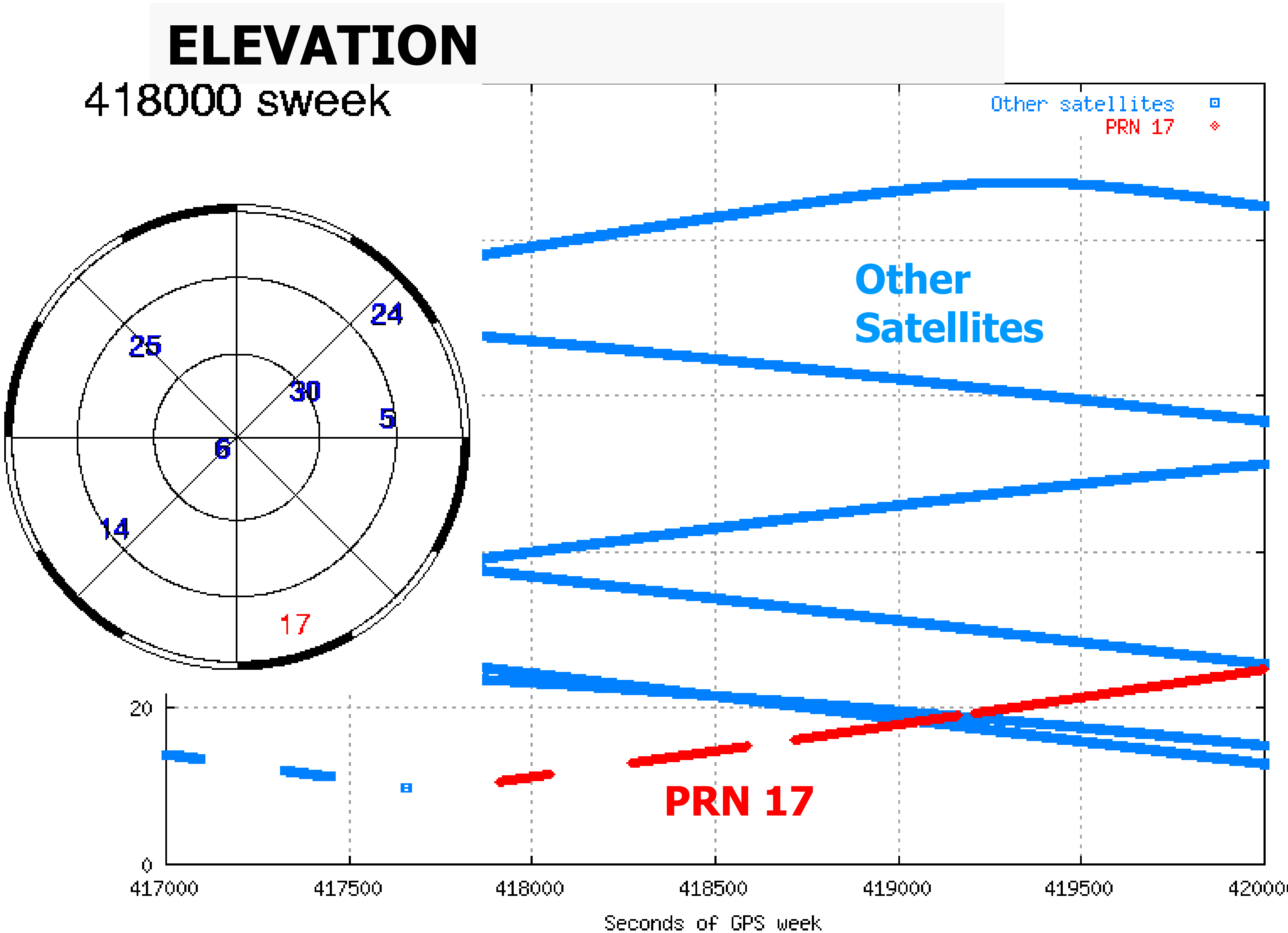
Sep 12th 2002 MI analysis



Sep 12th 2002 MI analysis



Sep 12th 2002 MI analysis



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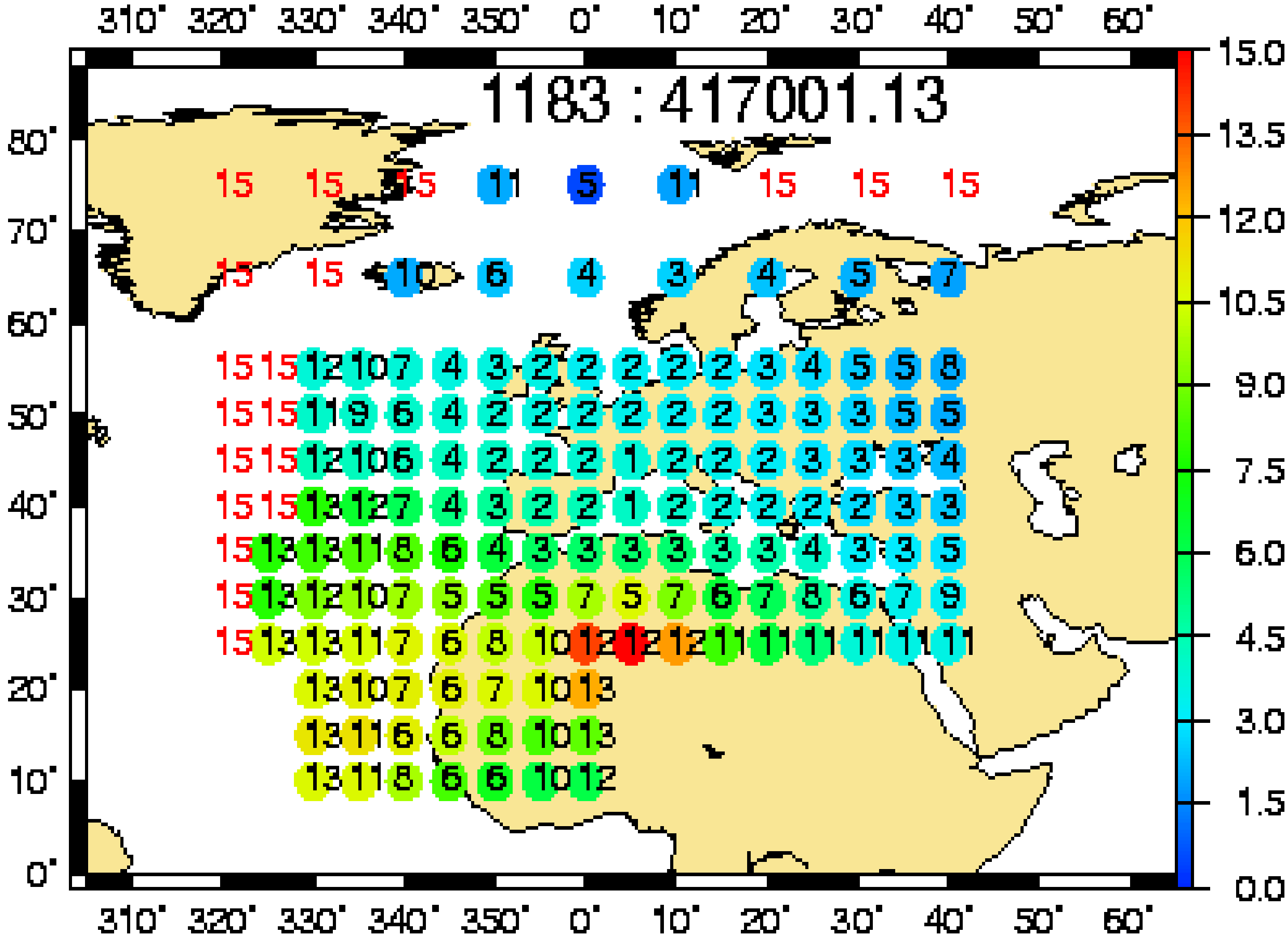
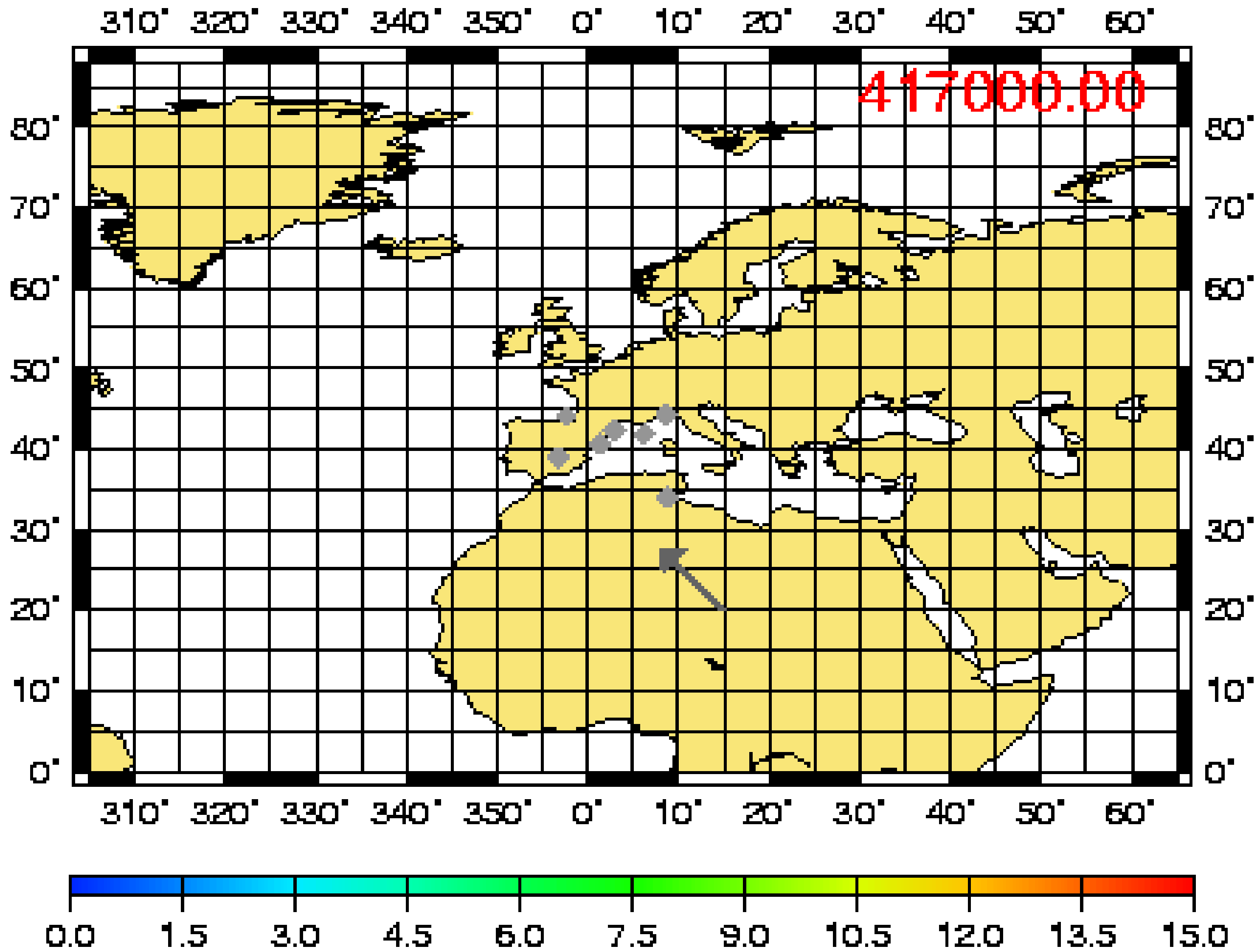
Sep 12th 2002 MI analysis

418000



Sep 12th 2002 MI analysis

418000



PART III

EGNOS and Civil Aviation

Civil Aviation Navigation

- VFR : Visual Flight Rules

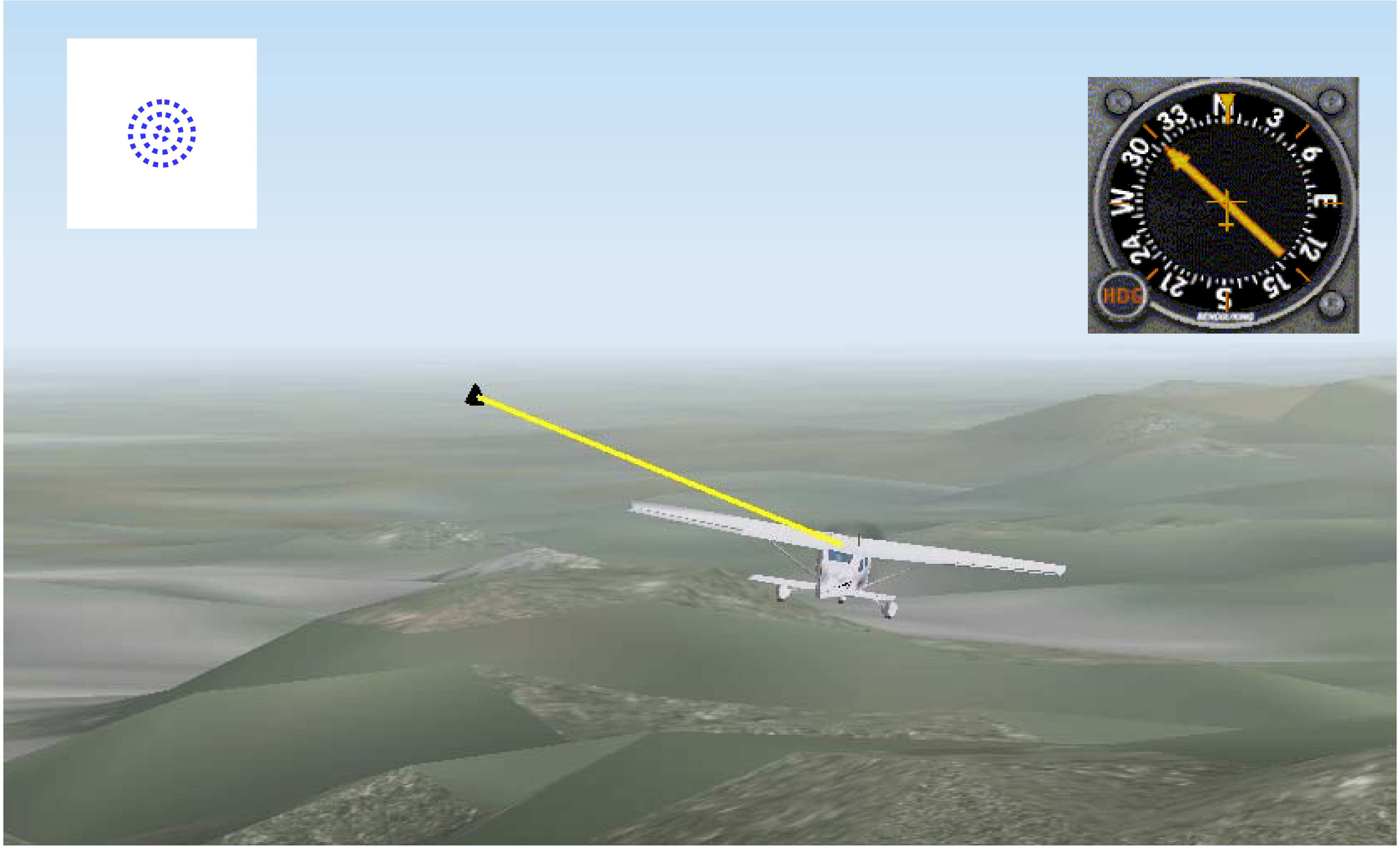
  Visibility better than 5 Km – 8 Km

- IFR : Instrumental Flight Rules

  Radionavigation Aids

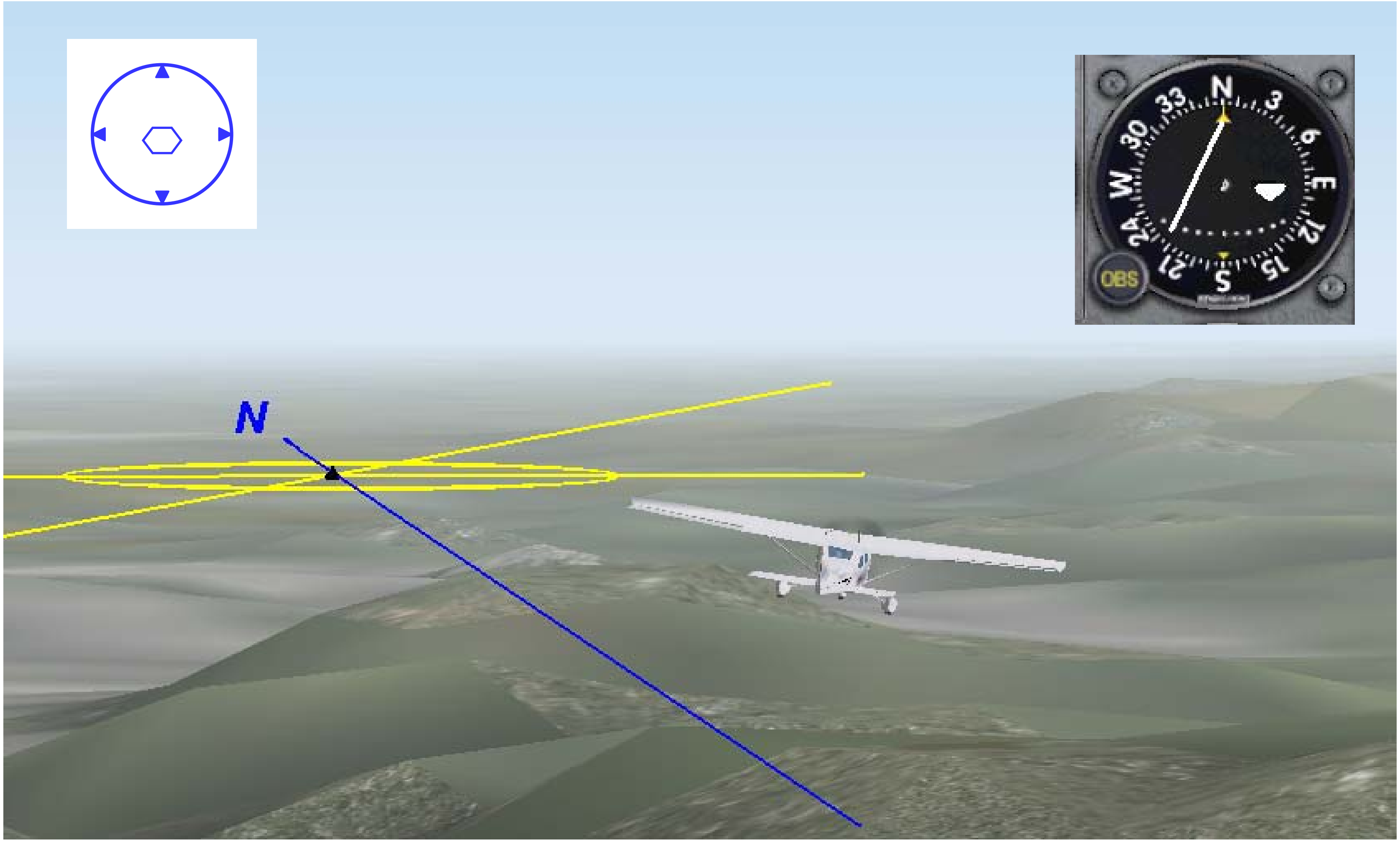
Radionavigation Aids

Non Directional Beacon (NDB)



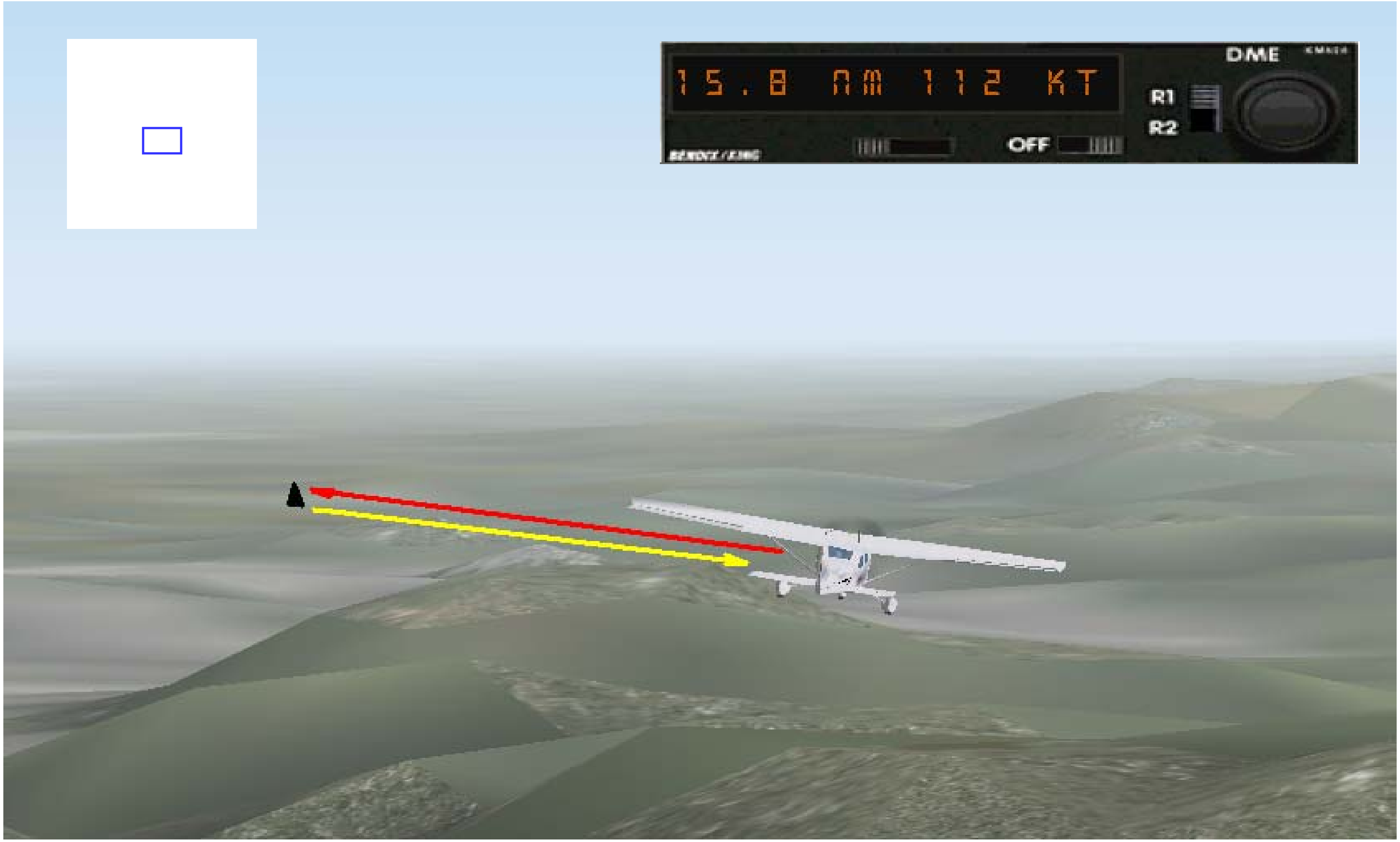
Radionavigation Aids

VHF Omnidirectional Ranger (VOR)



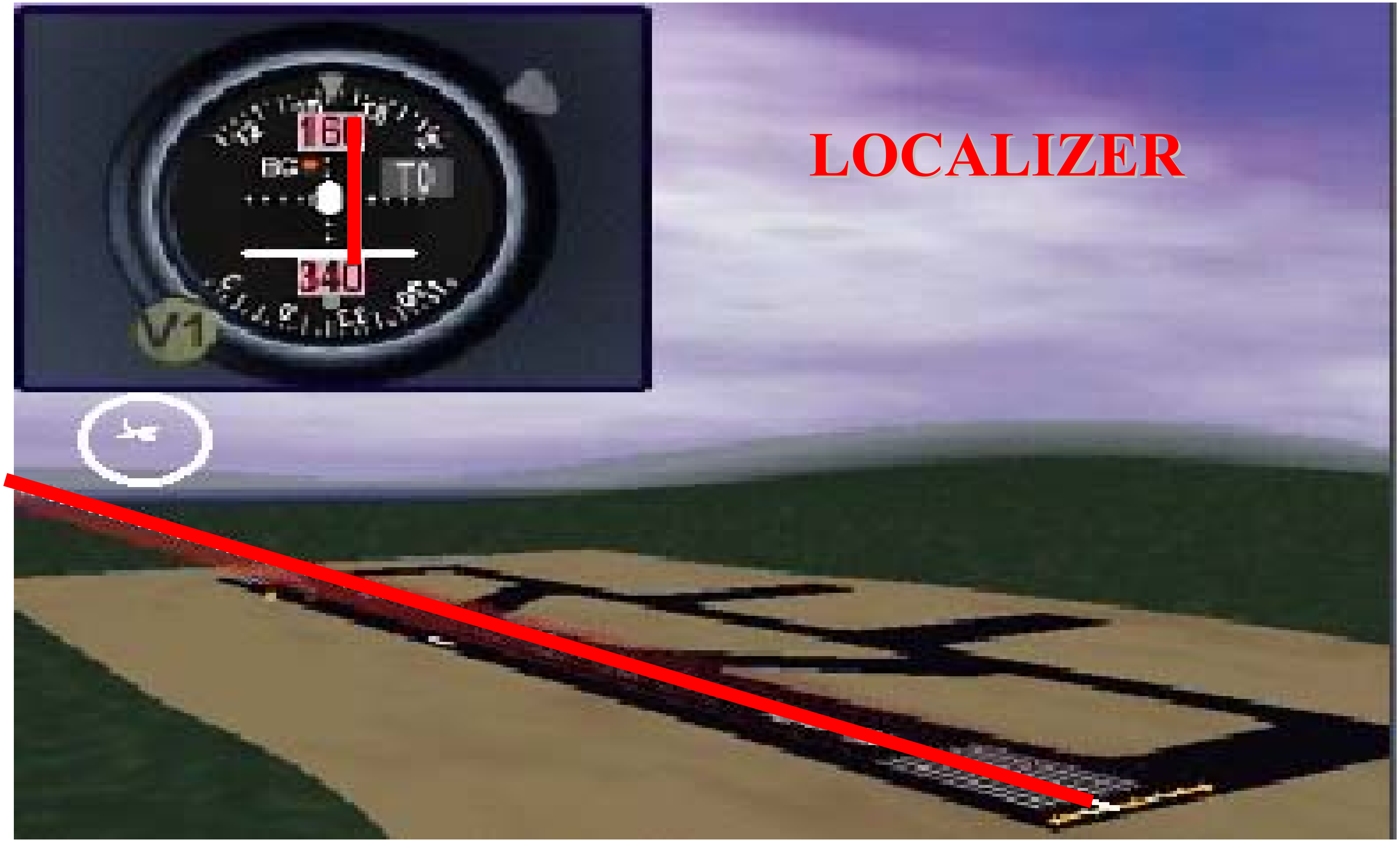
Radionavigation Aids

Distance Measuring Equipement (DME)



Radionavigation Aids

Instrumental Landing System (ILS)

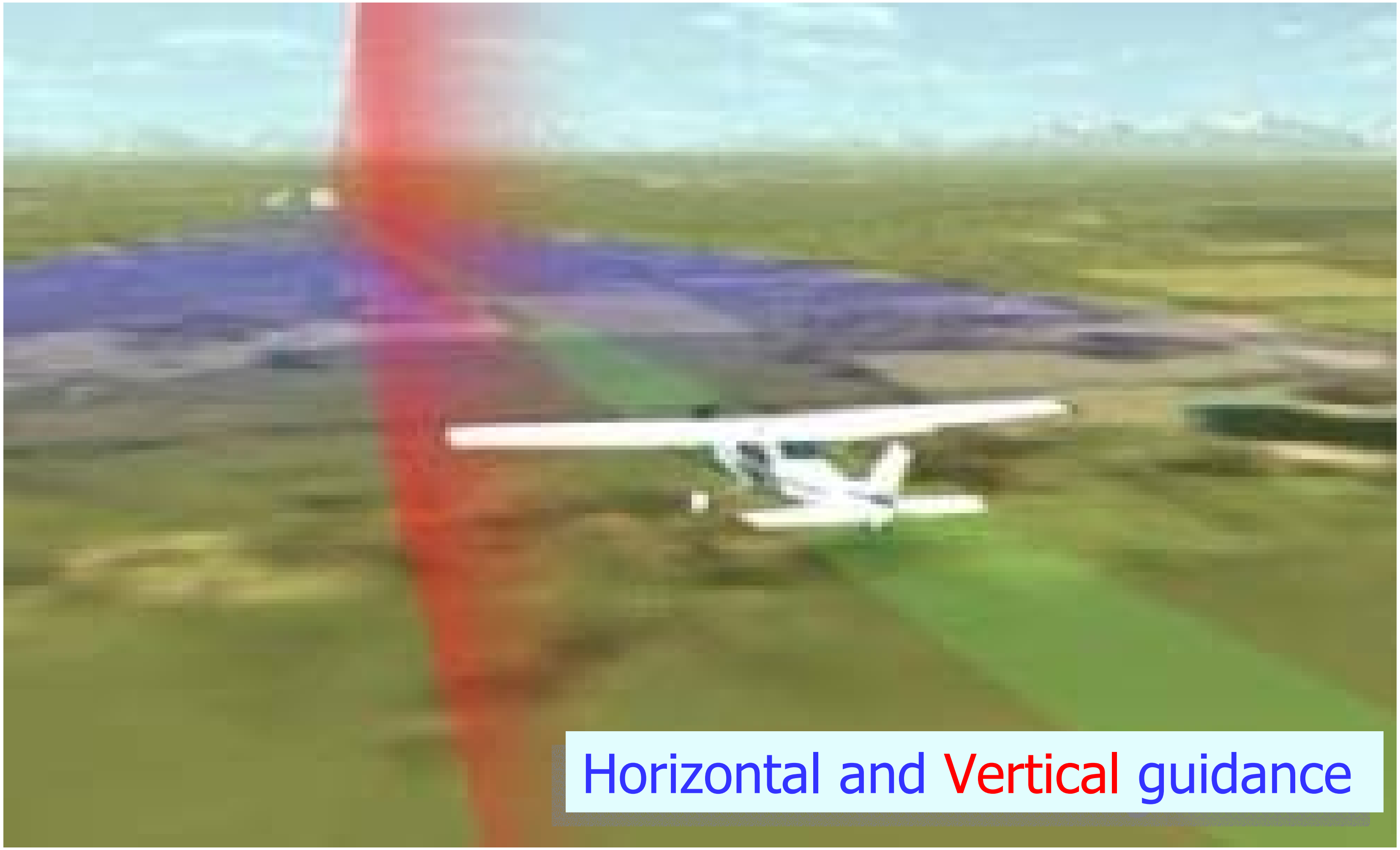


Radionavigation Aids

Instrumental Landing System (ILS)

Radionavigation Aids

Instrumental Landing System (ILS)



Radionavigation Aids

Radar Vectoring

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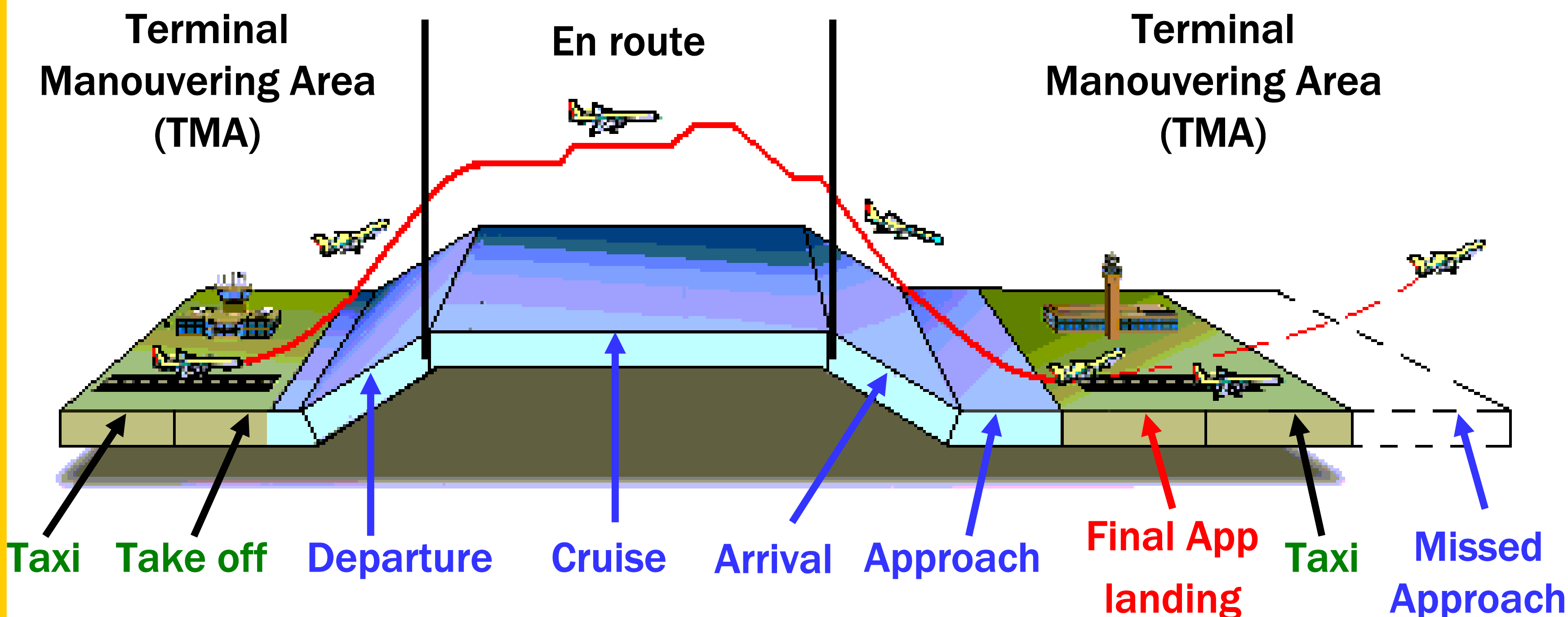
Phases of flight



VOR
DME
NDB
Radar Vectoring

2D

VOR
DME
NDB

Non Precision

2D

ILS **Precision**

3D

UPC

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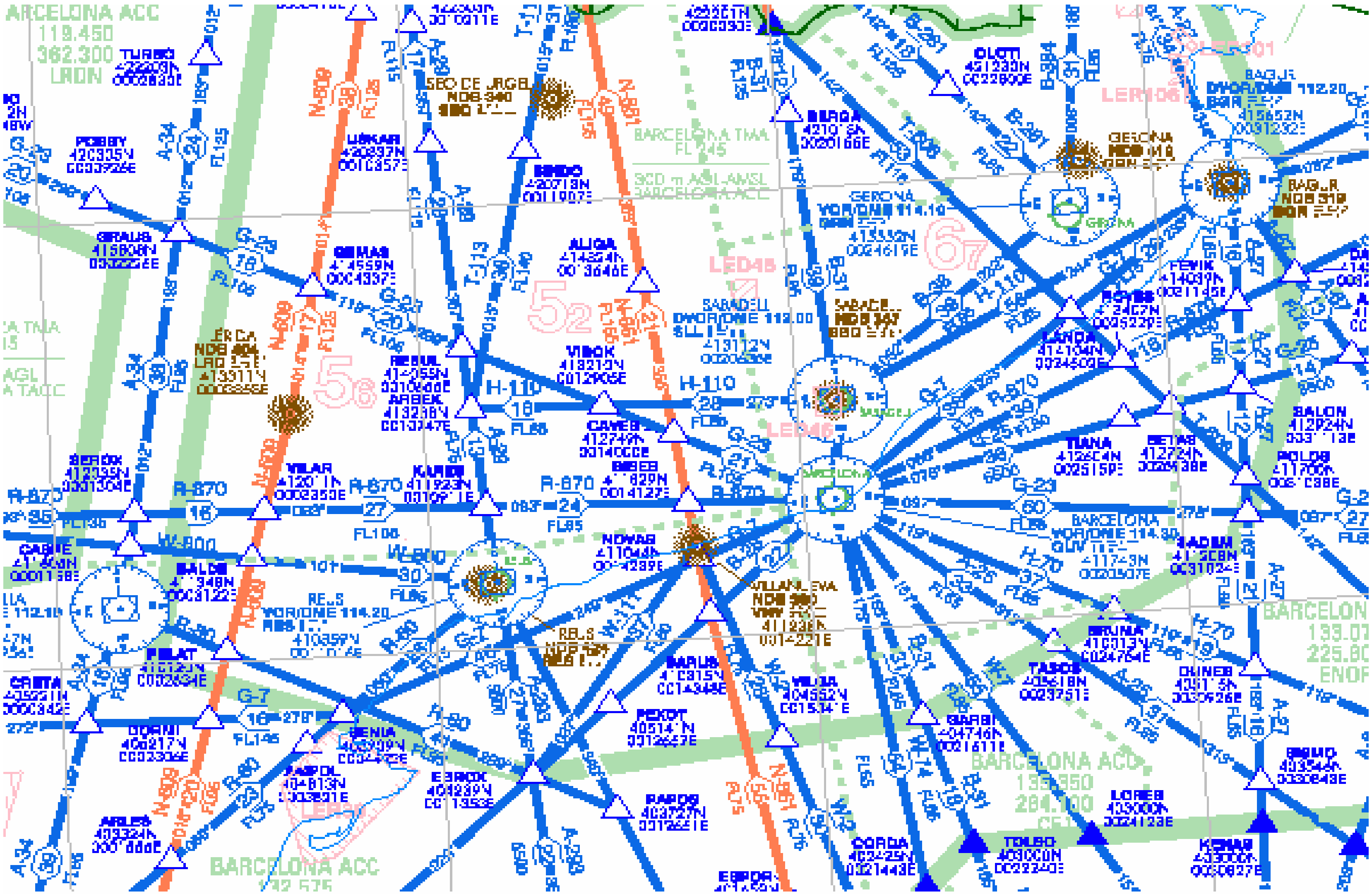
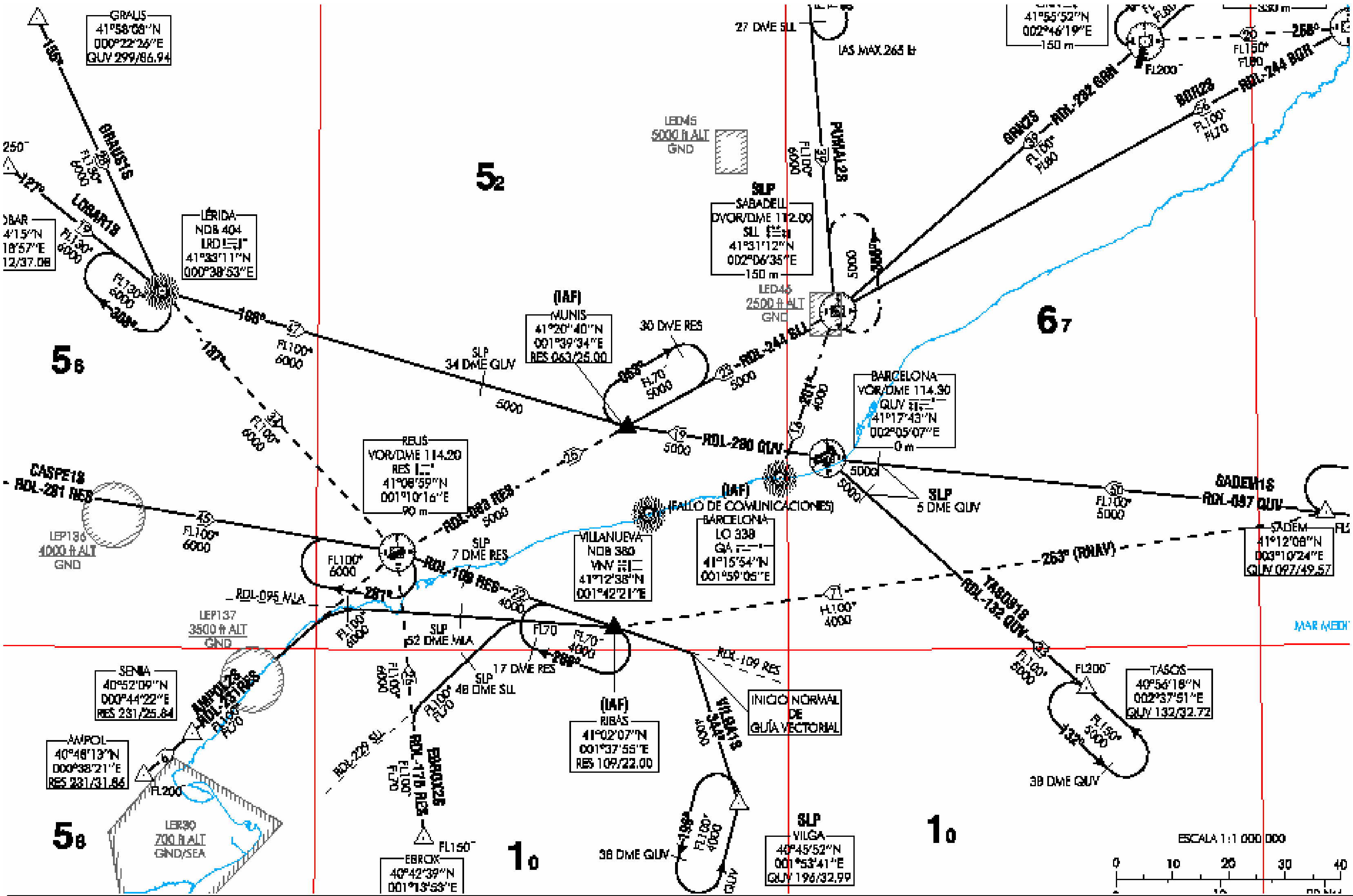
IFR Cruise

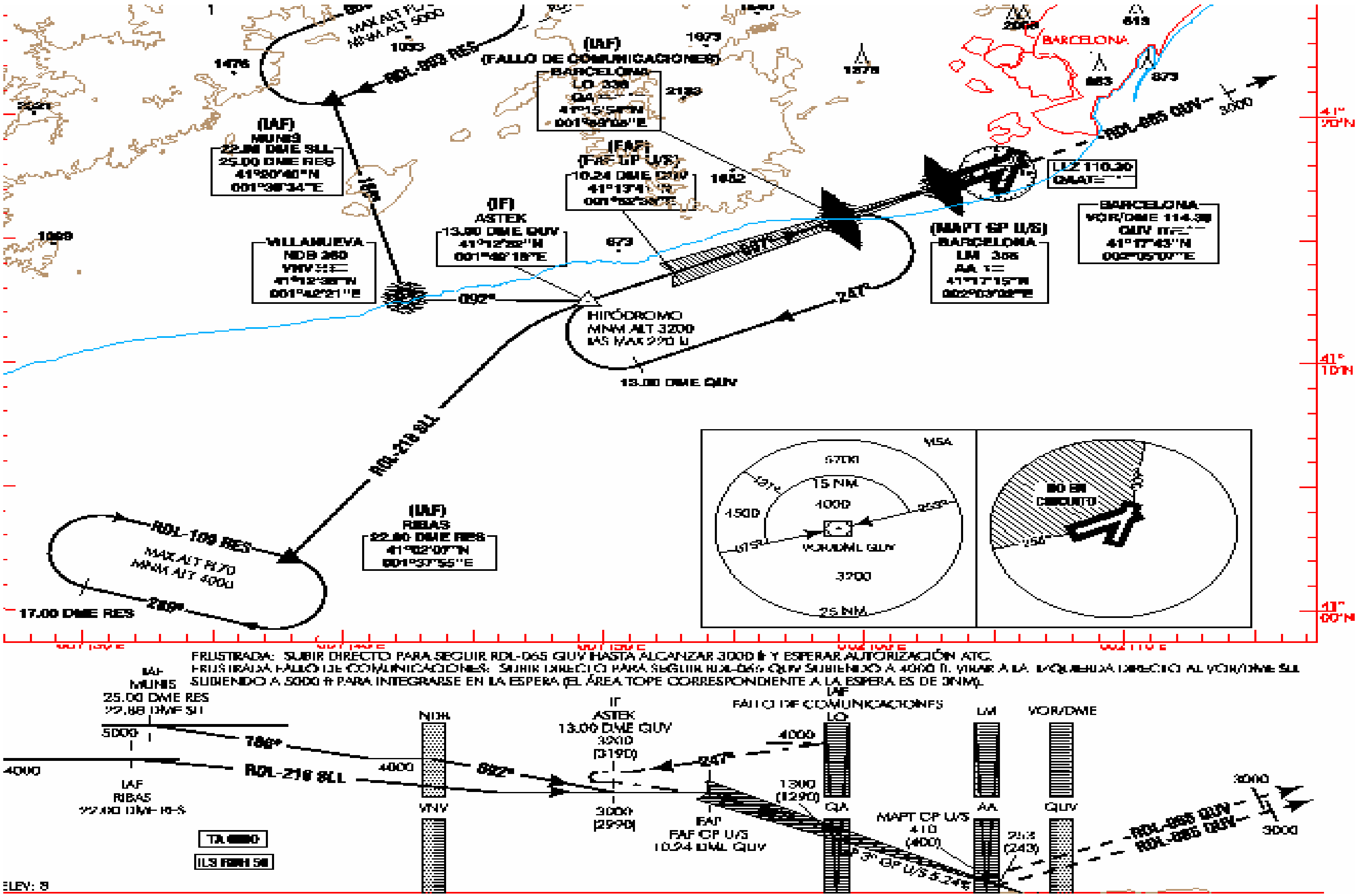


IFR Arrivals



Manuel Hernández-Pajares, J. Miguel Juan, Jaume Sanz, Xavier Prats, February 2002.

IFR Approach



Avionics

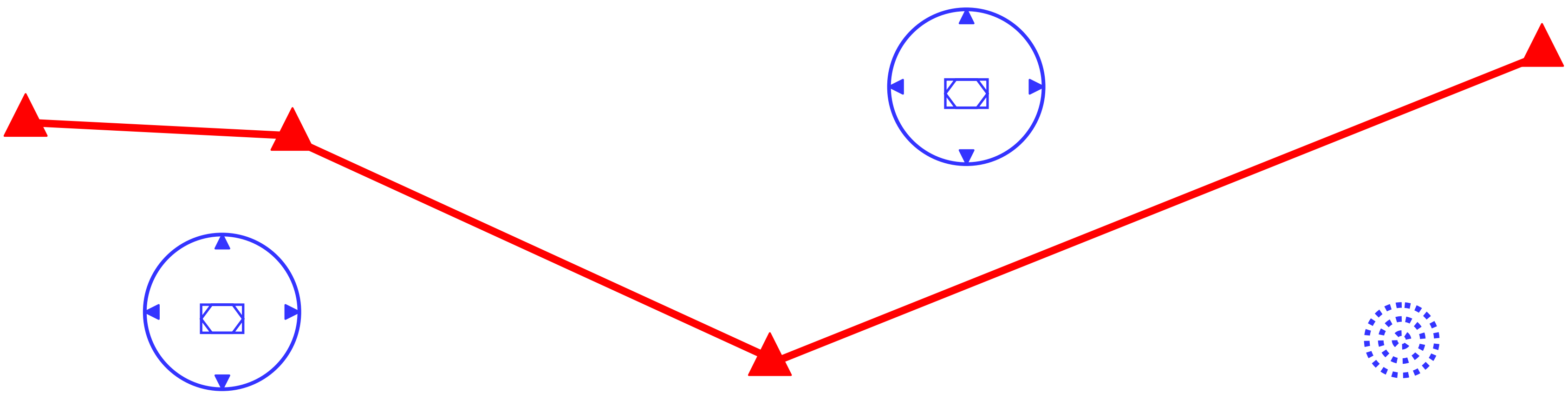
Avionics


GS 225 TAS 253
060 / 70
VOR APP
EPR 193°
2.2NM
10 : 46
RBT300
FL110
EPR

RNAV concept

- RNAV = Area Navigation

  Navigation using flight tracks joining ANY two points without the need for the overfly of specific ground facilities.



Basic RNAV (B-RNAV) = +/- 5NM accuracy

Precision RNAV (P-RNAV) = +/- 1NM accuracy

RNAV concept

- RNAV = Area Navigation

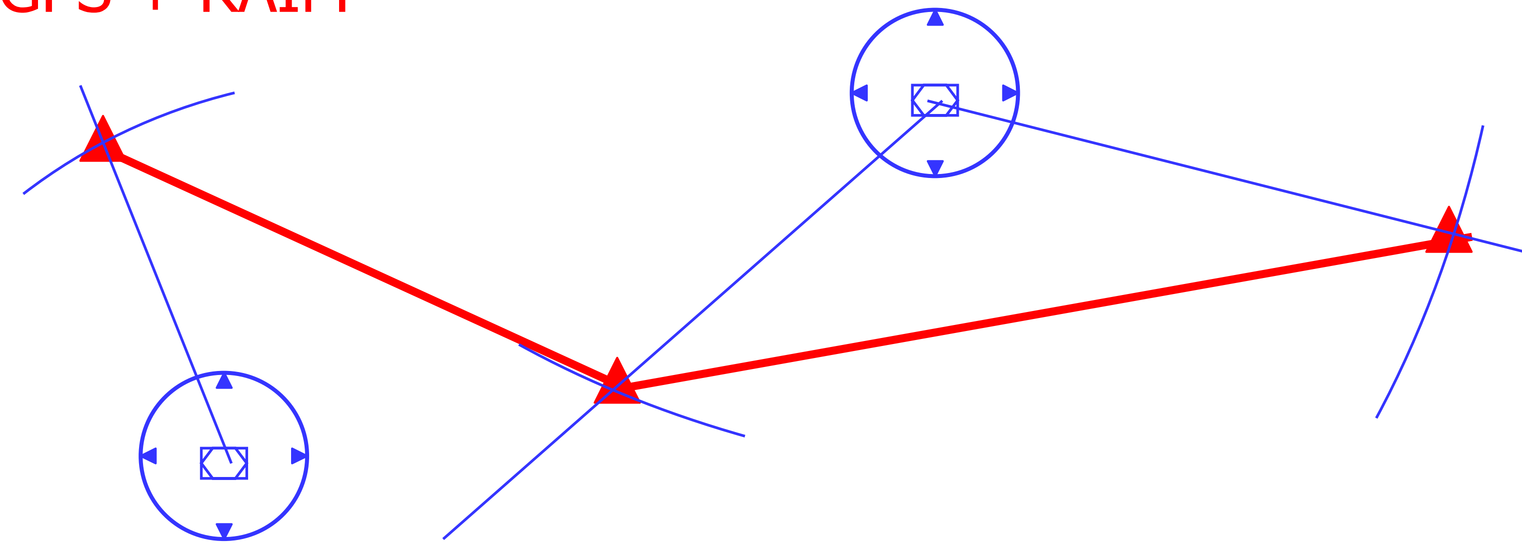
  Navigation using flight tracks joining ANY two points without the need for the overfly of specific ground facilities.

- More flexibility
- Less fuel consumption
- Delay reduction (bottle necks)
- Noise reduction

RNAV concept

RNAV (Area Navigation)

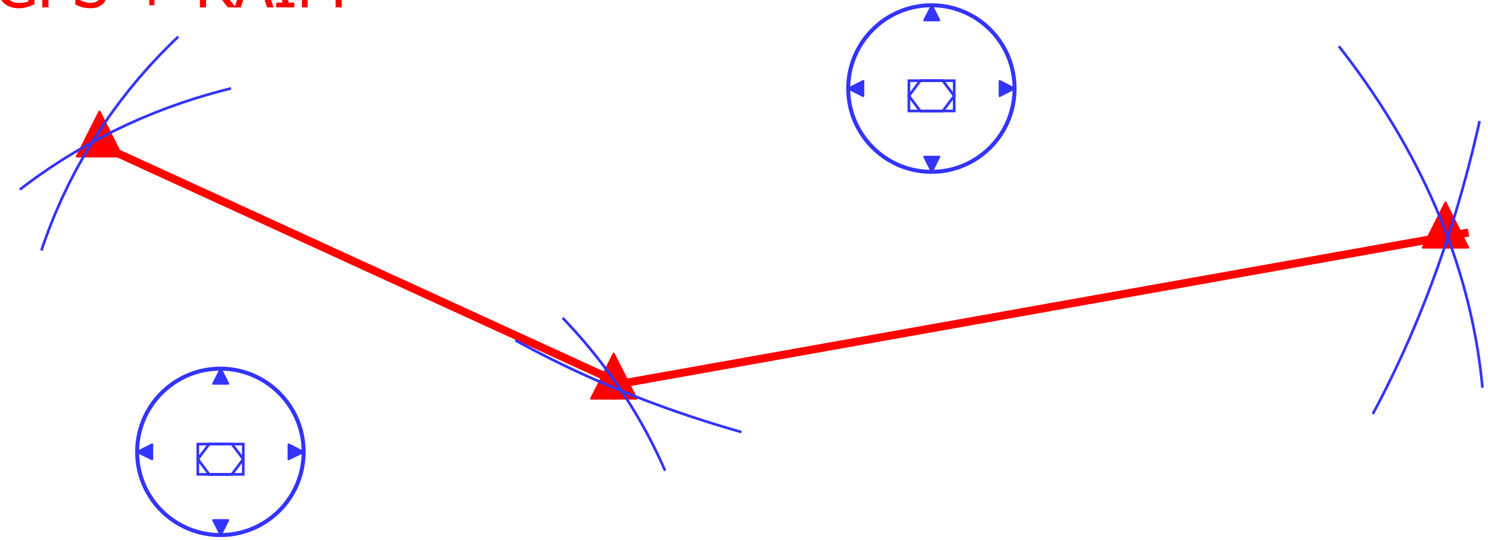
- VOR/DME
- DME/DME
- INS
- LORAN C
- GPS + RAIM



RNAV concept

RNAV (Area Navigation)

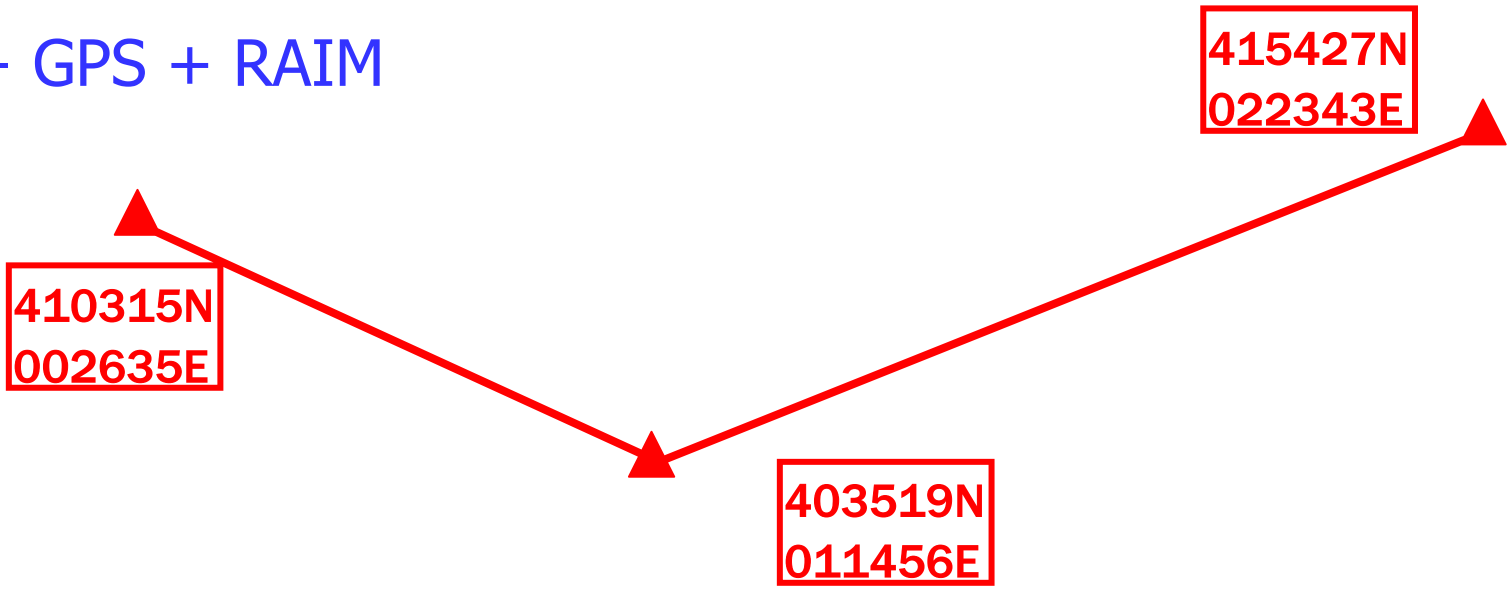
- VOR/DME
- DME/DME
- INS
- LORAN C
- GPS + RAIM



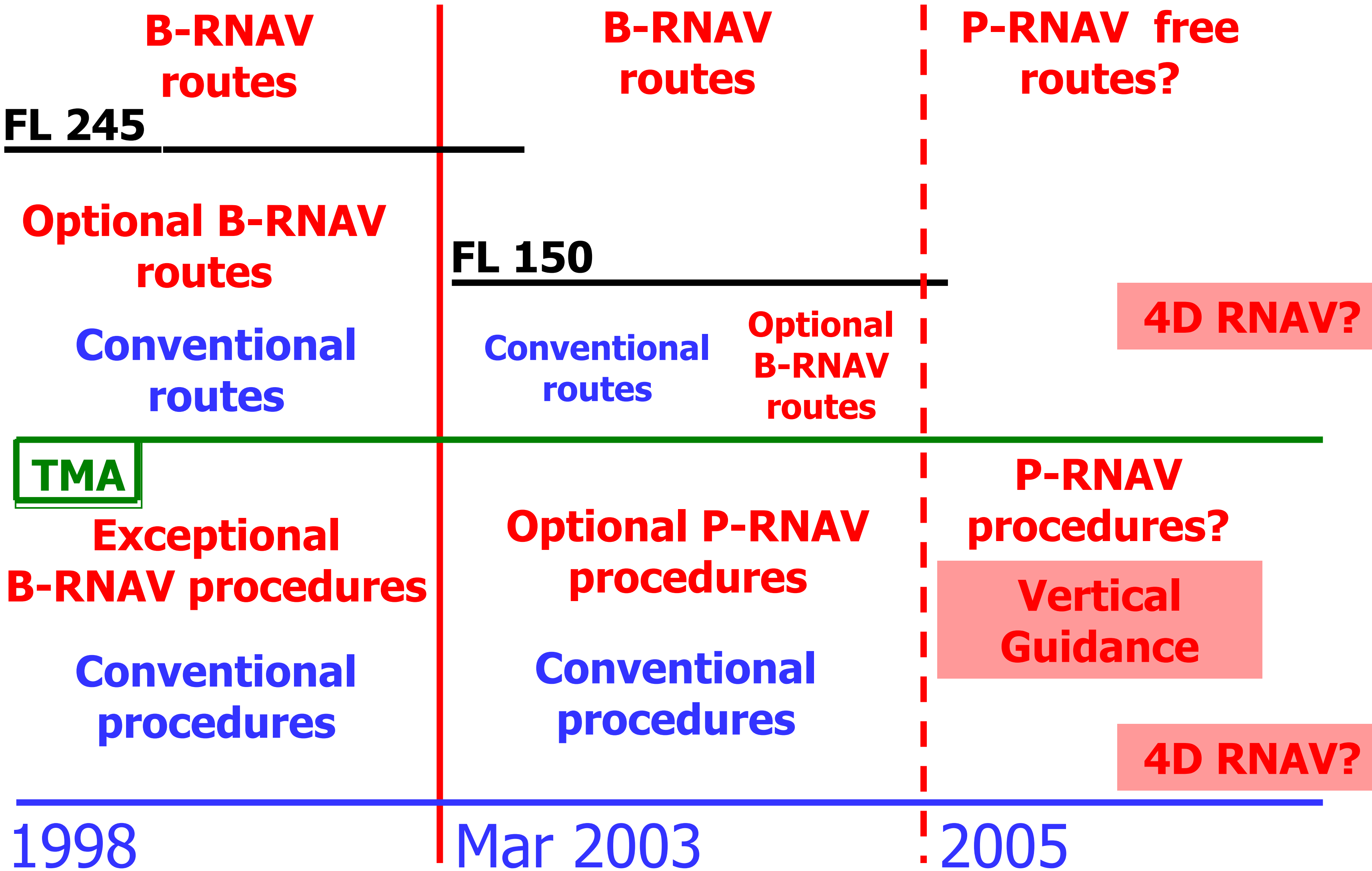
RNAV concept

RNAV (Area Navigation)

- VOR/DME
- DME/DME
- INS
- LORAN C
- GPS + RAIM



RNAV application (spain)



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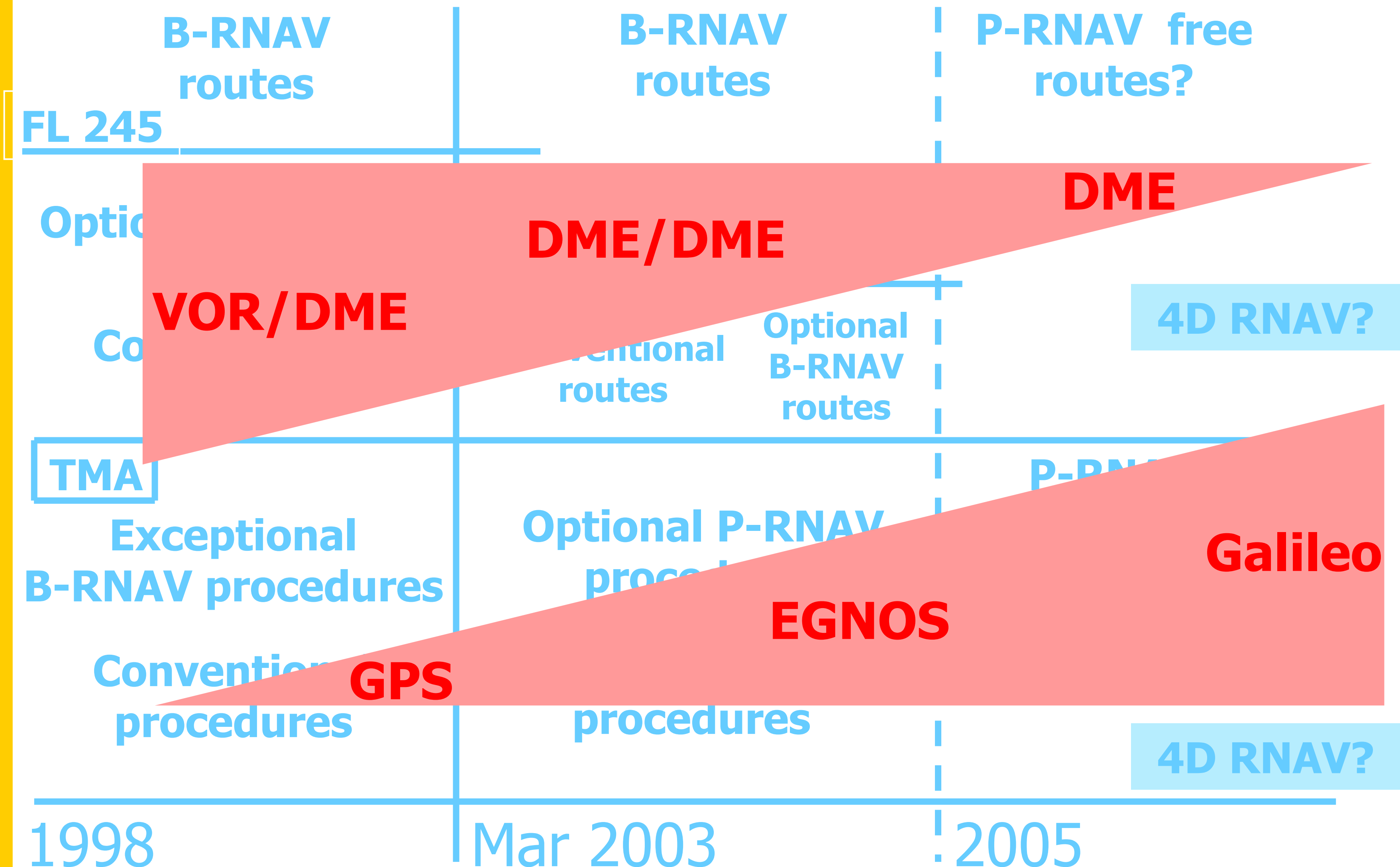
RNAV application (spain)



Vertical Guidance

Nowadays RNAV procedures are only 2D

For precision approaches Vertical Guidance is also needed

	Decision Height	Visibility
CAT - I	200 ft (60m)	> 800 m
CAT - II	100 ft (30m)	> 400 m
CAT - III	100 ft - 0 ft *	> 400 m - 0 m *

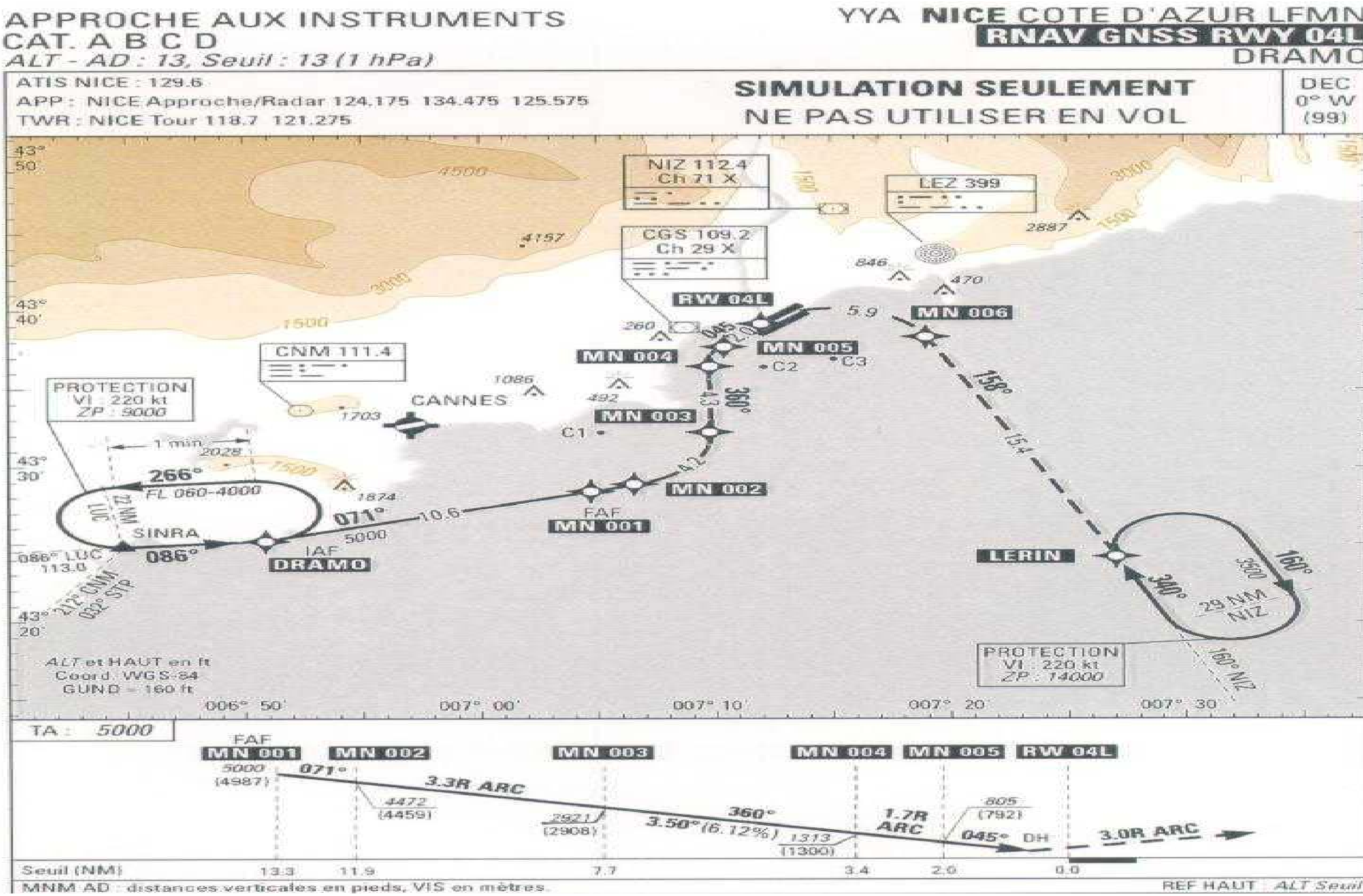
* Variable in function of aircraft , crew, airport facilities,... certification

Vertical Guidance

EGNOS is designed to meet P-RNAV with vertical guidance (APV)

ILS	EGNOS
Very precise approaches: **CATI, CATII, CATIII**	**CAT-I performnances**
Straight approaches	**Curved approaches**
Local coverage	**Global coverage with constant accuracy**

Example: Nice approaches



See [3]: Approaching Nice with the EGNOS System Test Bed. Satellite Navigation and Positioning world show, NavSat 2001

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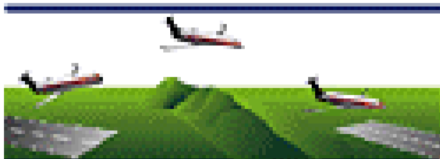
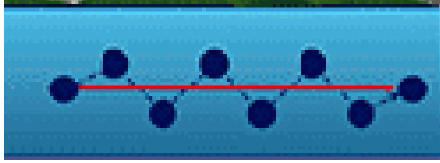
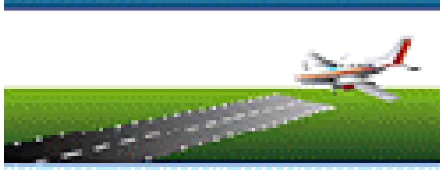
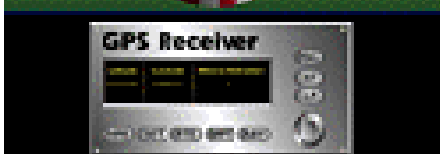
Benefits of EGNOS in Civil Aviation

	Primary Means of Navigation - Take-Off, En Route, Approach and Landing
	More Direct Routes-Not Restricted by Location of Ground-Based Navigation Equipment
	Precision Approach Capability-At any Qualified Airport in U.S.
	Decommissioning of Older, Expensive Ground-Based Navigation Equipment
	ReducedSimplified Equipment on Board Aircraft
	Increased Capacity-More Aircraft Allowed in Given Airspace Without Increased Risk

Bibliography

1. J. Ventura-Travesset, P. Michael and L. Gautier, 2001. Architecture, Mission and signal processing aspects of the EGNOS System: the first European implementation of GNSS. http://esamultimedia.esa.int/docs/egnos/estb/Publications.
2. Todd Walter, 1999. WAAS MOPS: Practical Examples. ION National Technical Meeting Proceedings, Sant Diego, California, USA. http://waas.stanford.edu/.
3. S. Soley, E. Breeuwer, R. Farnworth, J.P. Dupont, Y. Coutier, 2001, Approaching Nice with the EGNOS System Test Bed. Satellite Navigation and Positioning world show, NavSat 2001. http://www.eurocontrol.fr/projects/sbas.
4. Minimum Operational Performances Standards for Global Positioning System / Wide Area Airborne Equipment. RTCA/Doc 229A, June 1998.
5. M. Hernández-Pajares, J.M. Juan and J. Sanz, 2002. GPS Data processing: Code and Phase. Algorithms, Techniques and Recipes. http://gage1.upc.es (in Spanish and English)
6. M. Hernández-Pajares, J.M. Juan and J. Sanz, X. Prats, J. Baeta. Basic Research Utilities for SBAS (BRUS). V Geomatics Week. Barcelona, 2003.

Acknowledgments

We acknowledge to EUROCONTROL for providing the ESTB data sets used in the ESTB performance examples.


That’s all,
Thank you
for your attention!