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Lecture 12

Augmentation systems

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Authorship statement

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Augmentation Systems

1. Introduction
2. Ground-Based Augmentation System (GBAS)
3. Satellite-Based Augmentation System (SBAS)

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Introduction: 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

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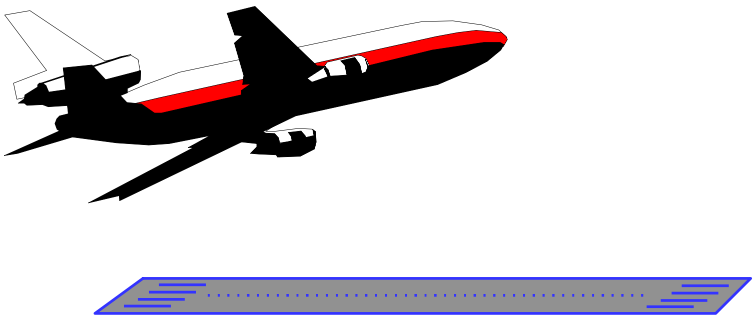
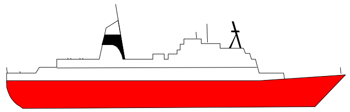
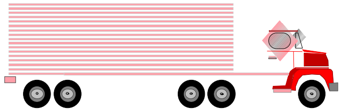
Why Augmentation Systems?

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



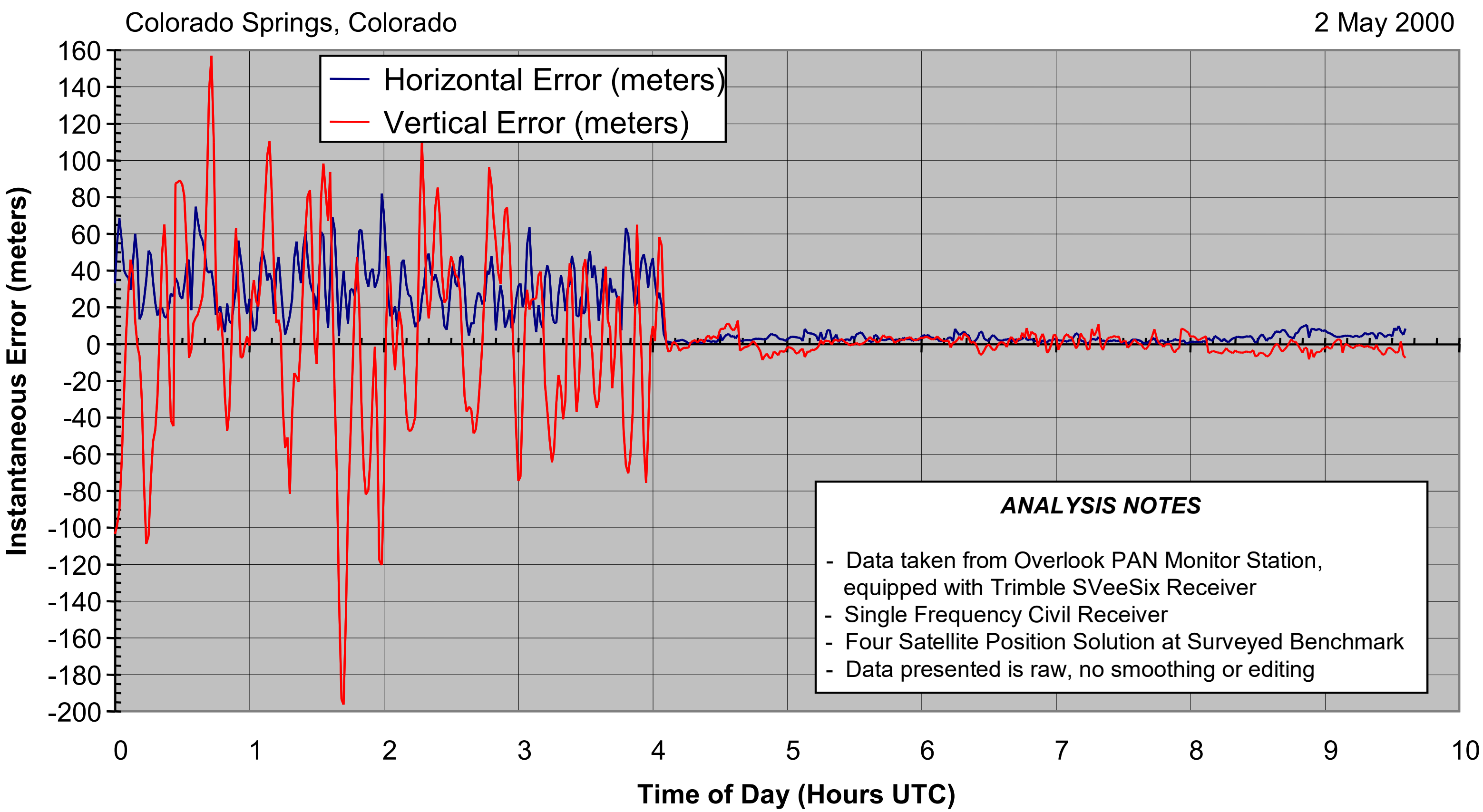
- Marine and land users also require some sort of augmentation for improving the GPS/ GLONASS performances.





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

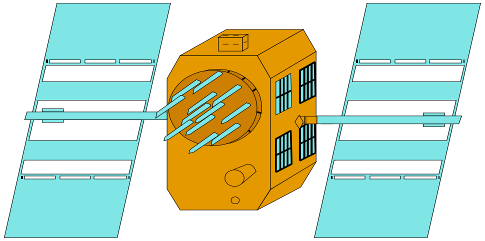
Even with S/A off a Vertical Accuracy < 4m 95% of time cannot be guaranteed with the standalone GPS.



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:

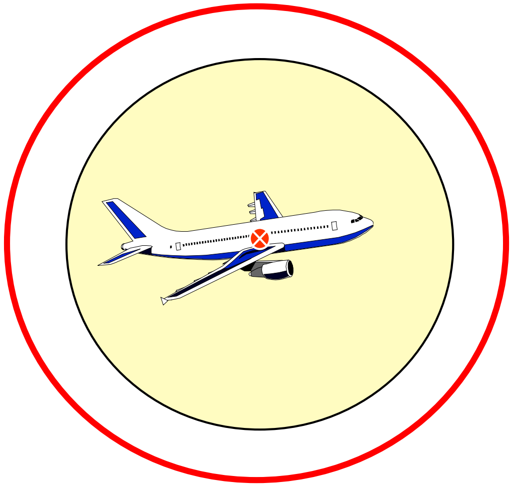
GPS up to 2 hours late

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



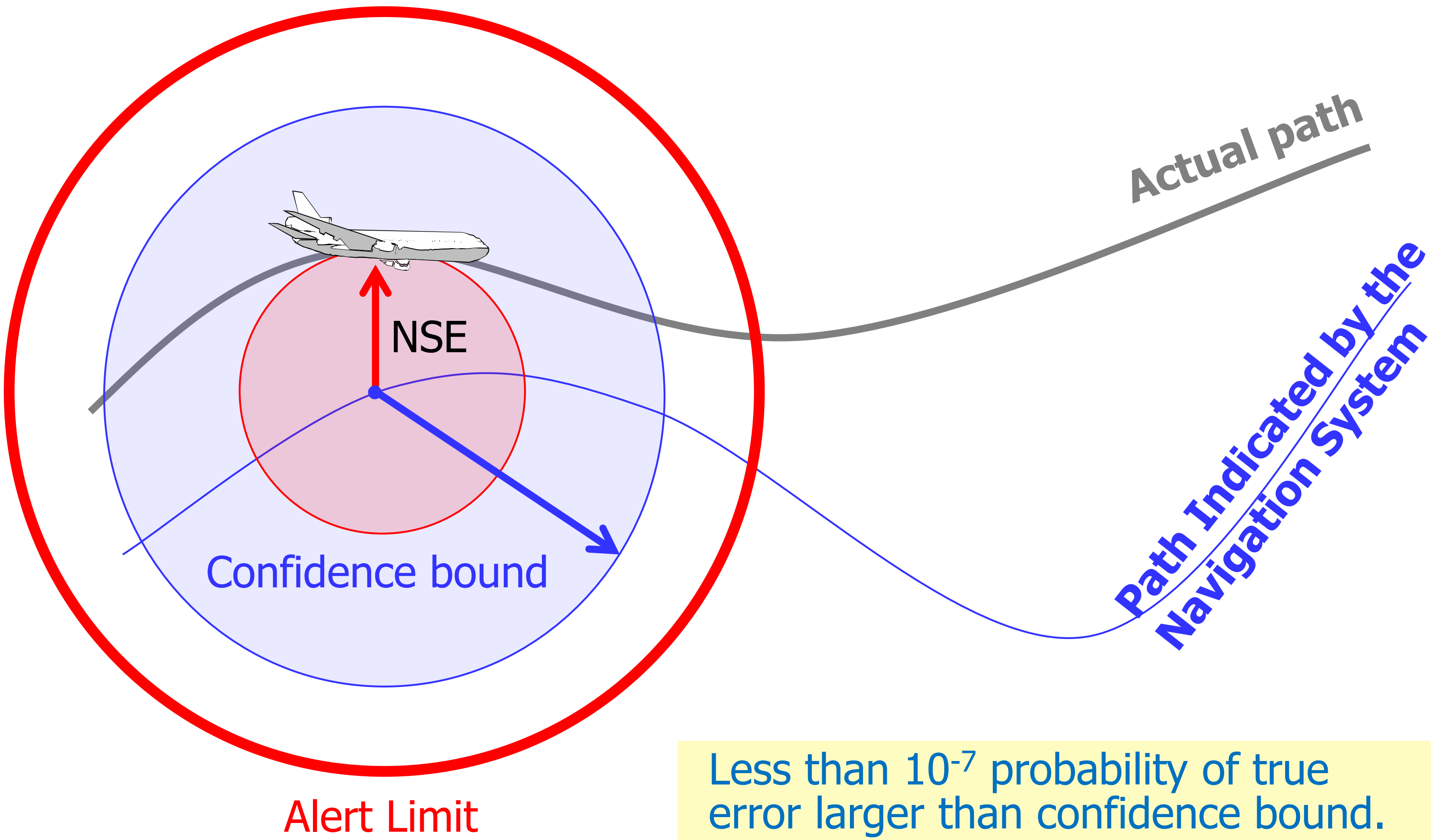
Continuity:

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

GPS PERFORMANCE LIMITATIONS: INTEGRITY
MAIN GPS POTENTIAL INTEGRITY PROBLEMS

- Major GPS Ephemeris Errors (assumed ~10-4/hour)
- Out of Specification of on-board Clocks: Step Errors, Ramp Errors, or acceleration Errors (assumed ~10-4/hour/SV). Includes GPS Clock Drifts and GPS Clock Jumps.
- Signal Deformations/Distortions ("Evil Waveforms") (assumed ~10-4/hour/SV, although much lower in reality)
- GPS L1/L2 Hardware Bias (Jumps or Drifts) (assumed ~10-5/hour/SV)
- Code/Carrier Divergence (assumed ~10-5/hour/SV)
- Others (excessive phase noise carrier; GPS ICD violation; Corrupted nav message; etc)

Source: Javier Ventura-Traveset.
ESA/JRC International Summer school on GNSS 2015

EXAMPLE OF FEARED EVENTS SPECIFICATIONS ERRONEOUS GPS EPHEMERIS

4.1.12 Erroneous GPS Ephemeris

The feared event associated to Erroneous GPS Ephemeris is:

GPS-EFE-12: Erroneous GPS Ephemeris
A single GPS satellite provides a valid ephemeris before time T0 and provides an ephemeris not compliant to GPS ephemeris accuracy requirement after T0.
A GPS ephemeris is not compliant to the accuracy requirement if the 3D ephemeris error is more or equal to 78 m.

Occurrence probability:

$1*10^{-4}$/hour/SV

Source: Javier Ventura-Traveset.
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GPS INTEGRITY FAILURES
EXAMPLE: PRN 23 ANOMALY ON JAN. 1, 2004

- GPS Block II-A-10 Satellite SVN-23 Suffered an Integrity Failure on 01 Jan 04
  - Operating on a Rubidium clock
  - Clock failed at about 18:30 UTC (Holiday Afternoon)
  - Clock failure caused a substantial frequency error
  - An integrity failure because no timely warning issued

- GPS Operations Set SVN-23 Unhealthy at about 21:18 UTC (i.e after 2h and 48 minutes)
  - Accumulated pseudorange error was about 285,000 m
  - SVN-23 remained trackable as PRN-23 until it was declared unhealthy

Source: Javier Ventura-Traveset.

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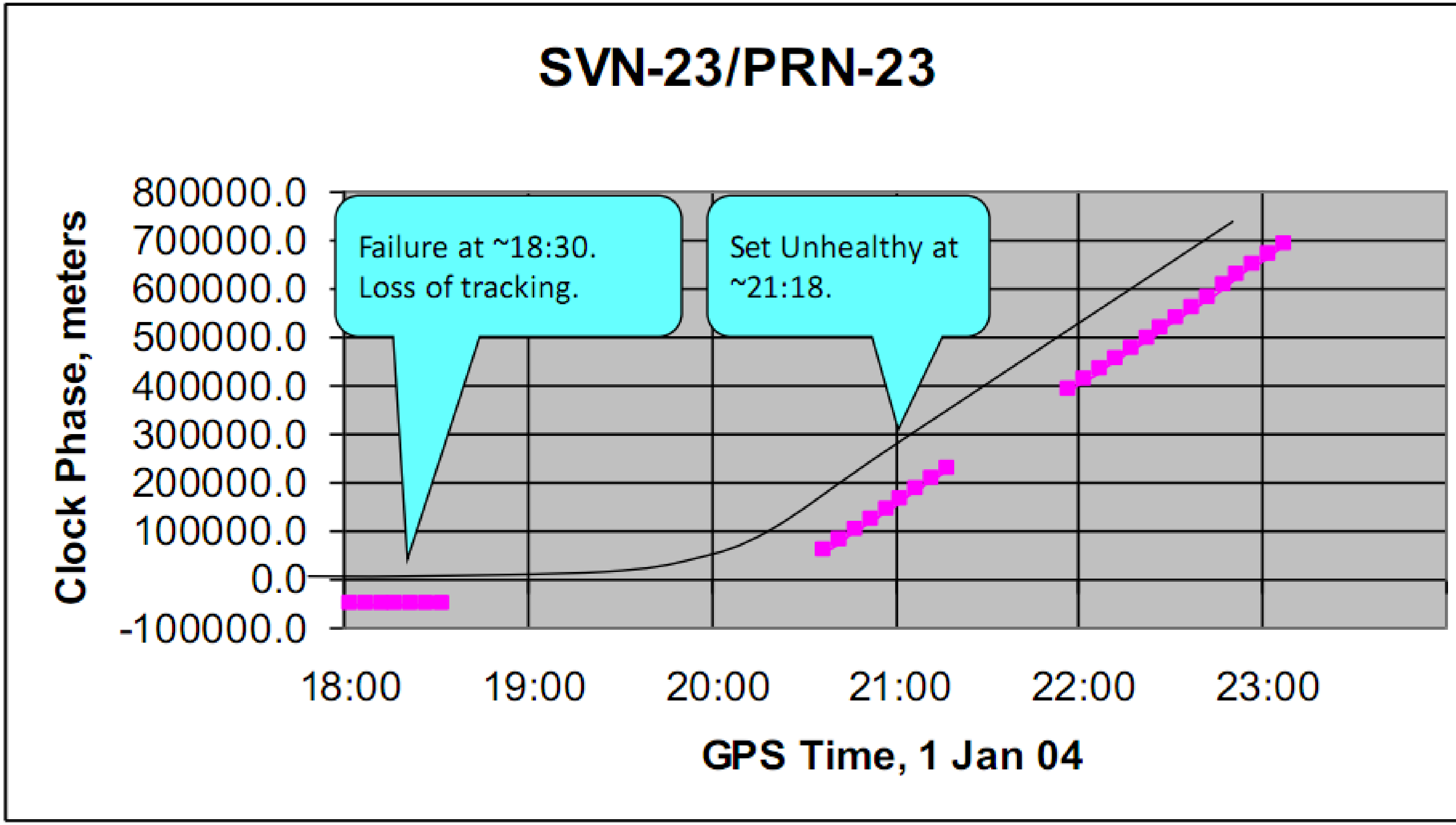
EXAMPLE: SV-23 CLOCK ERROR ON JAN 1, 2004



Source: Javier Ventura-Traveset.

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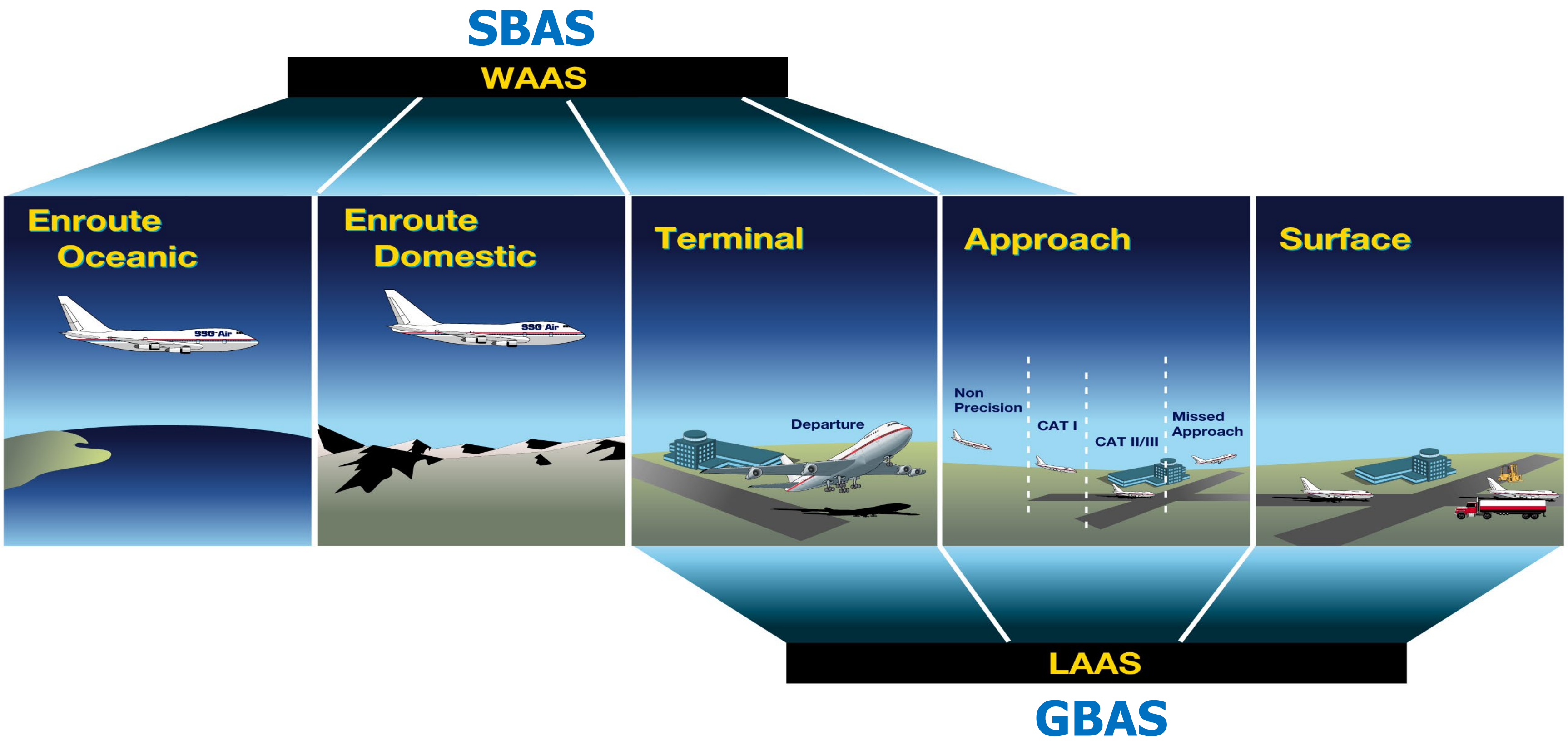
SBAS and GBAS Navigation Modes



ICAO SBAS REQUIREMENTS

Typical operation(s)	Accuracy lateral /vertical 95%	Alert limit lateral /vertical	Integrity	Time to alert	Continuity	Avail.
En-route	2.0 NM / N/A	4 NM / N/A	10^{-7}/h	5 min.	$1-10^{-4}$/h to $1-10^{-8}$/h	0.99 to 0.99999
En-route	0.4 NM / N/A	2 NM / N/A		15 s		0.999 to 0.99999
En-route, Terminal	0.4 NM / N/A	1 NM / N/A				
Initial approach, NPA, Departure	220 m/ N/A	0.3 NM / N/A		10 s		0.99 to 0.99999
APV-I	16 m / 20 m	40 m / 50 m	2x10-7 per approach		1-8x10-6 in any 15 s	
LPV-200	16 m / 4 m	40 m / 35 m		6 s		

Difficult to meet together

Differential Corrections and 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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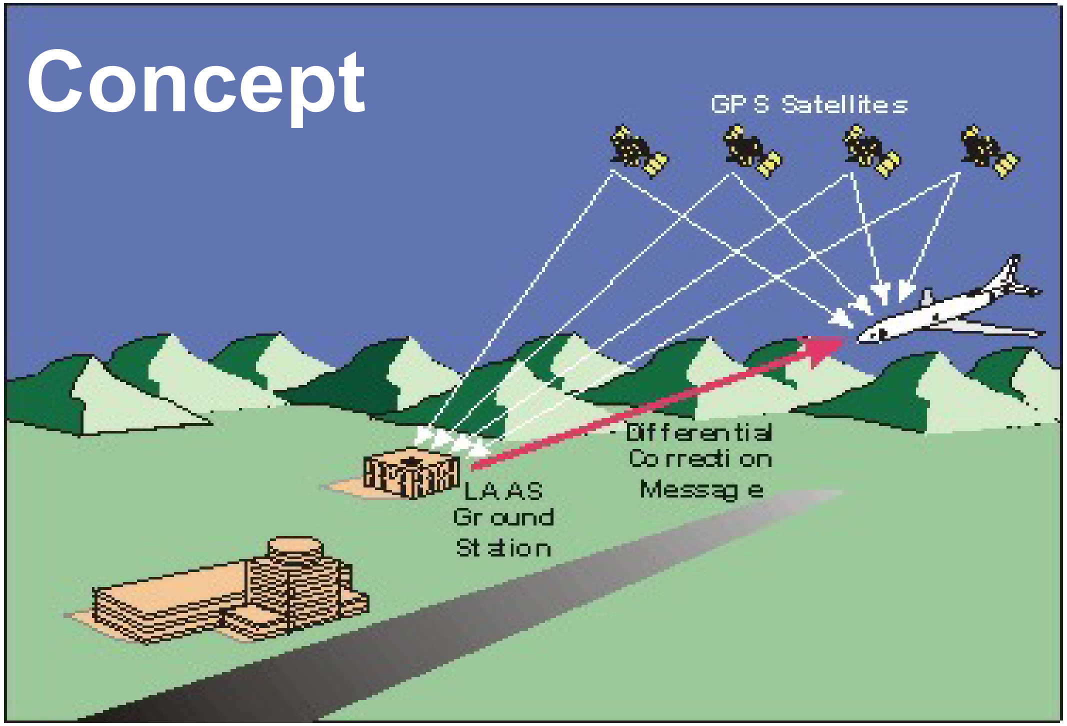
GBAS Concept

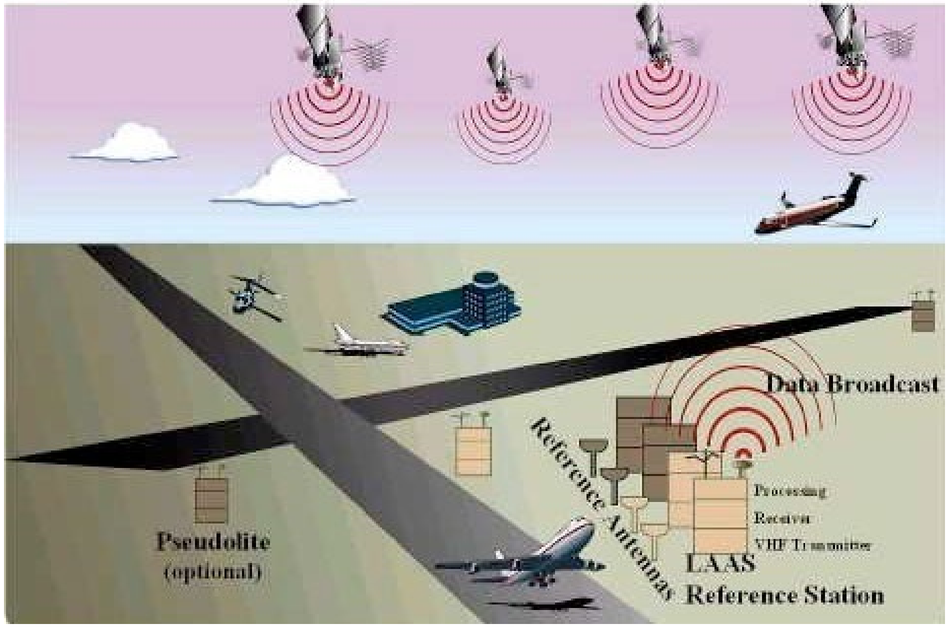


Most of the measurement errors are common:
clock, ephemeris, ionosphere and troposphere.

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).

GBAS Concept

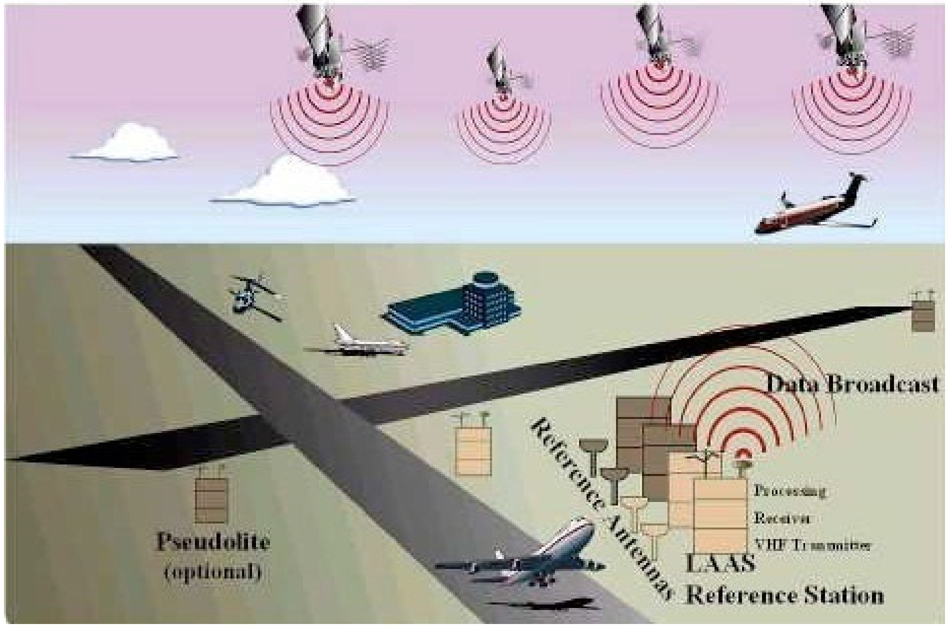


This system is used to support aircraft operations during approach and landing. The Ground Station (GS) responsible for generating and broadcasting carrier-smoothed code differential corrections and approach-path information to user aircrafts.

- It is also responsible of detecting and alarming space-segment and ground-segment failures.
- The GS must insure that all ranging sources for which GBAS corrections are broadcast are safe to use. If a failure occurs that threatens user safety, the GS must detect and alert users (by not broadcasting corrections for the affected ranging source) within a certain time-to-alert.

This is from [RD-5]

GBAS Components



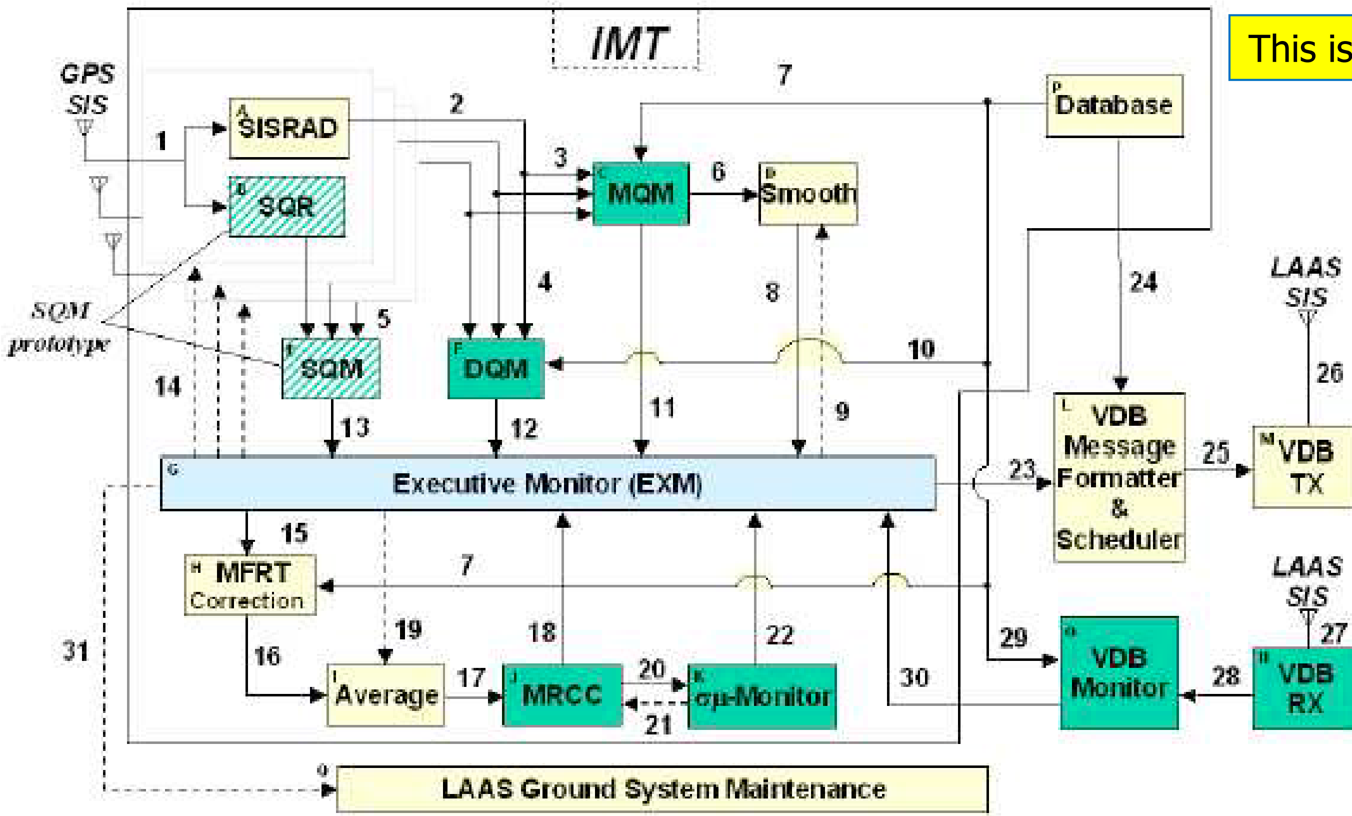
The GBAS station involves redundant Reference Receivers and antennas, redundant High Frequency Data Broadcast equipment linked to a single antenna.

- The GS tracks, decodes, and monitors GPS satellite information and generates differential corrections.
- It also performs integrity checks on the generated corrections.
- The correction message, along with suitable integrity parameters and approach path information, is then broadcast to airborne users on a VHF channel, up to about 40km.

This is from [RD-5]

Ground System Functional Flow Diagram

This is from [RD-5]



A variety of integrity monitor algorithms that are grouped into:

- Signal Quality Monitoring (SQM)
- Data Quality Monitoring (DQM)
- Measur. Quality Monitoring (MQM)
- Multiple Reference Consist Check (MRCC)
- σμ-monitor
- Message Field Range Test (MFRT)

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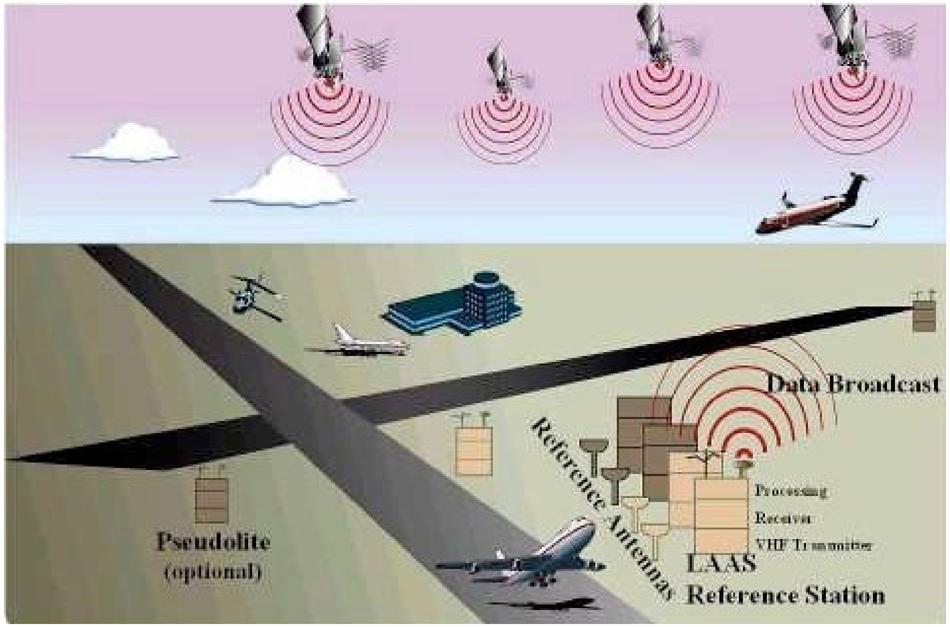

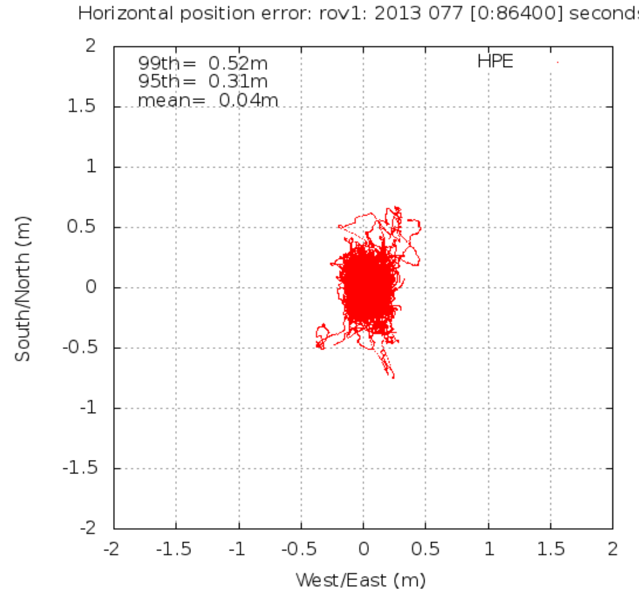

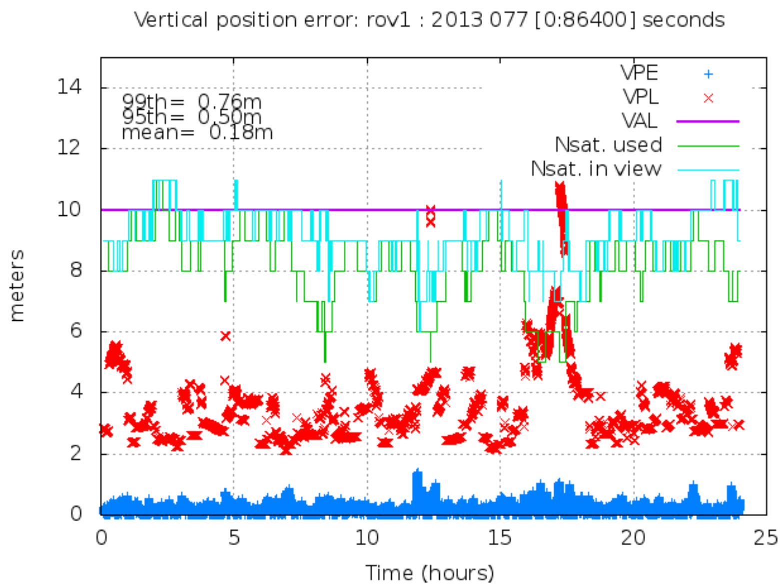

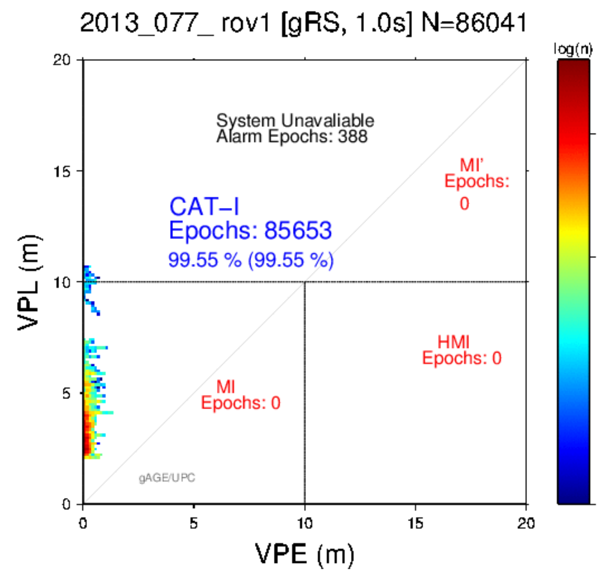

HOW MANY GBAS ARE NEEDED TO FILL EUROPE AS DONE BY SBAS?

- What is GBAS maximum range? There are three different effects to be considered:
  - VHF transmitter range;
  - Ionosphere error spatial decorrelation
  - other spatial decorrelation effects (e.g. ephemeris).
- Considering today's GBAS standards (GBAS ICD) the maximum GBAS range is limited by VHF transmission to about 40-50 Km.
- To fully cover Europe Land masses, about **600 GBAS would** be needed (vs **40 stations needed by EGNOS SBAS**)
- On the other hand, where needed GBAS may provided today enhanced performances than SBAS (e.g. CAT-1) – They are complementary

Source: Javier Ventura-Traveset.

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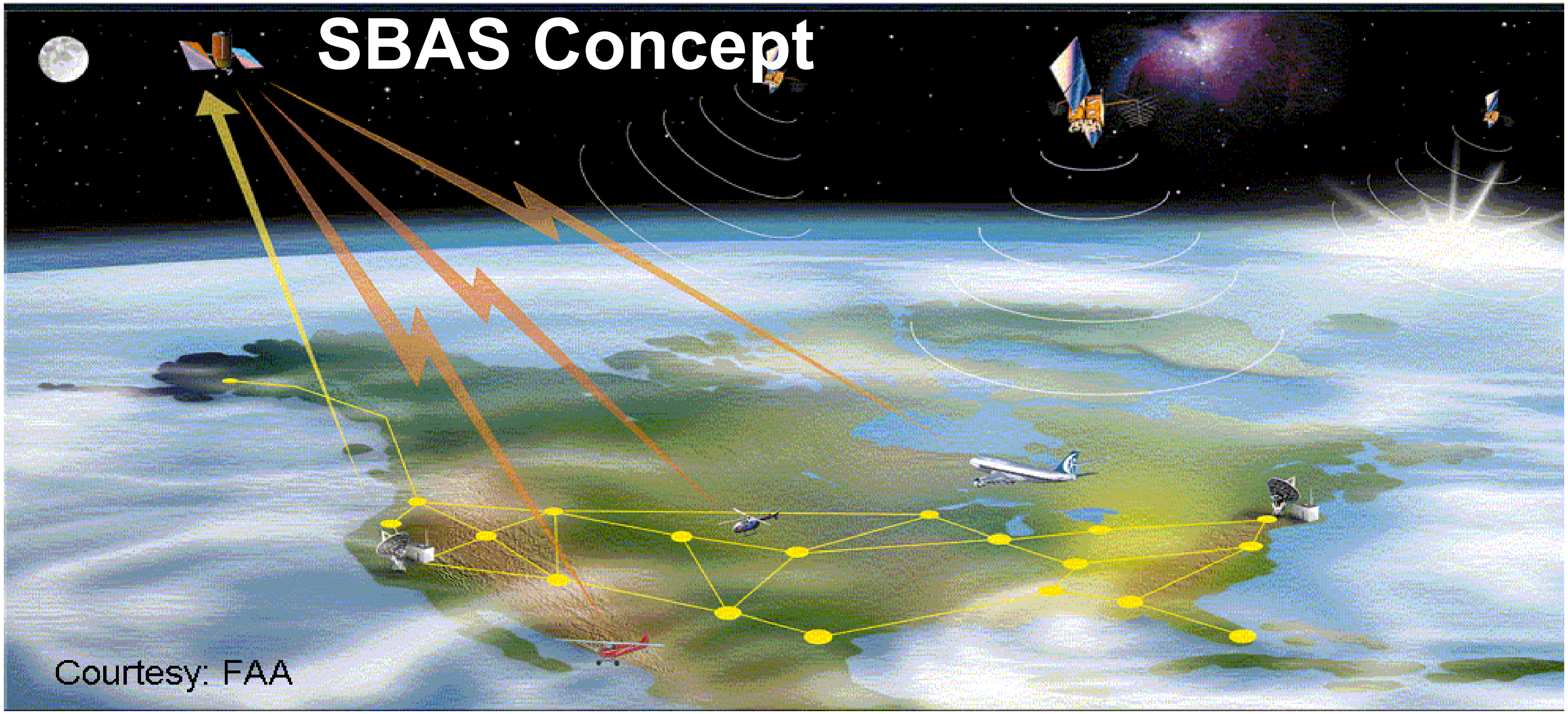
SBAS Concept

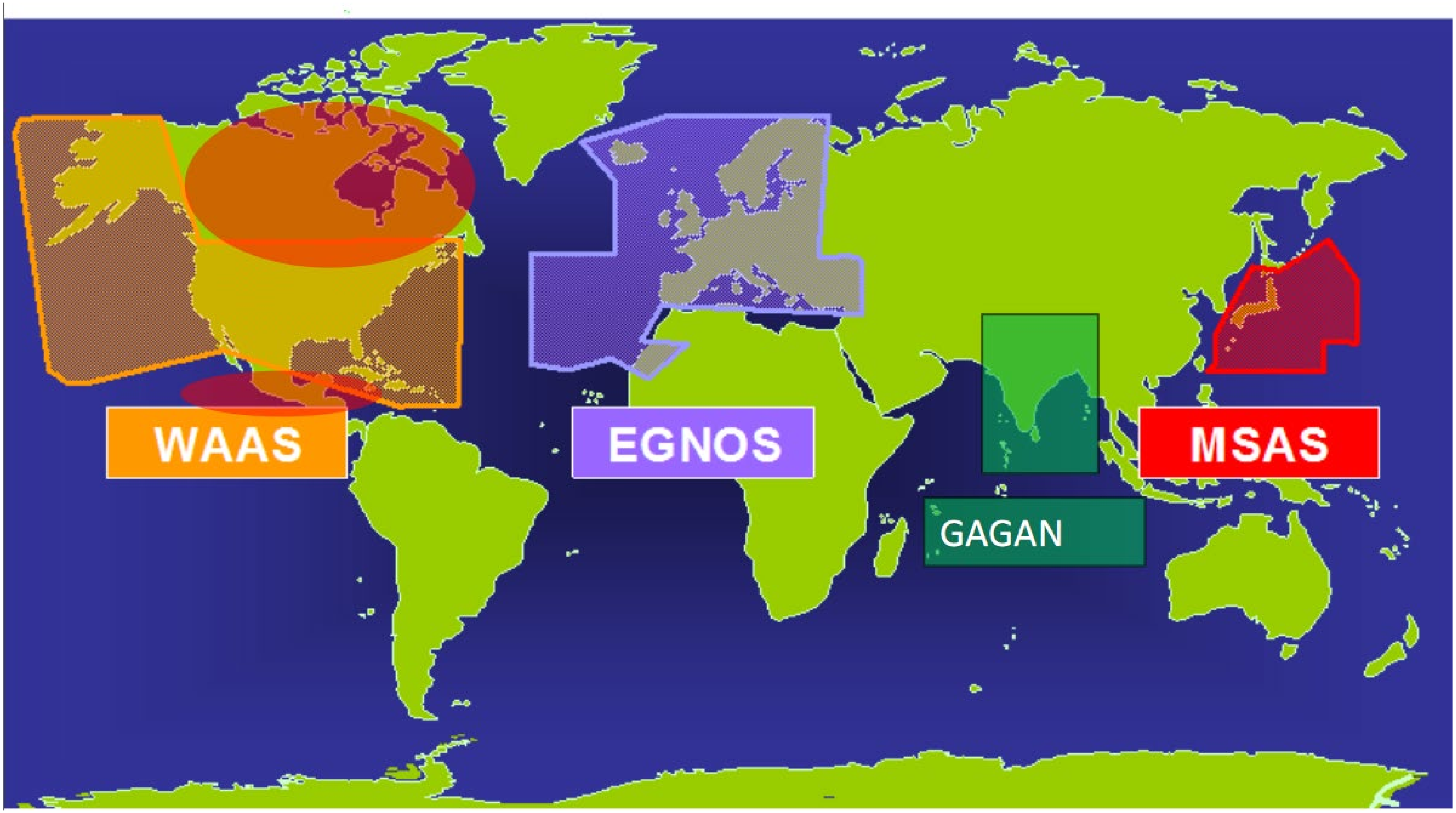


The pseurorange error is split in its components.

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

Uses a network of receivers to cover broad geographic area.

Today SBAS Systems



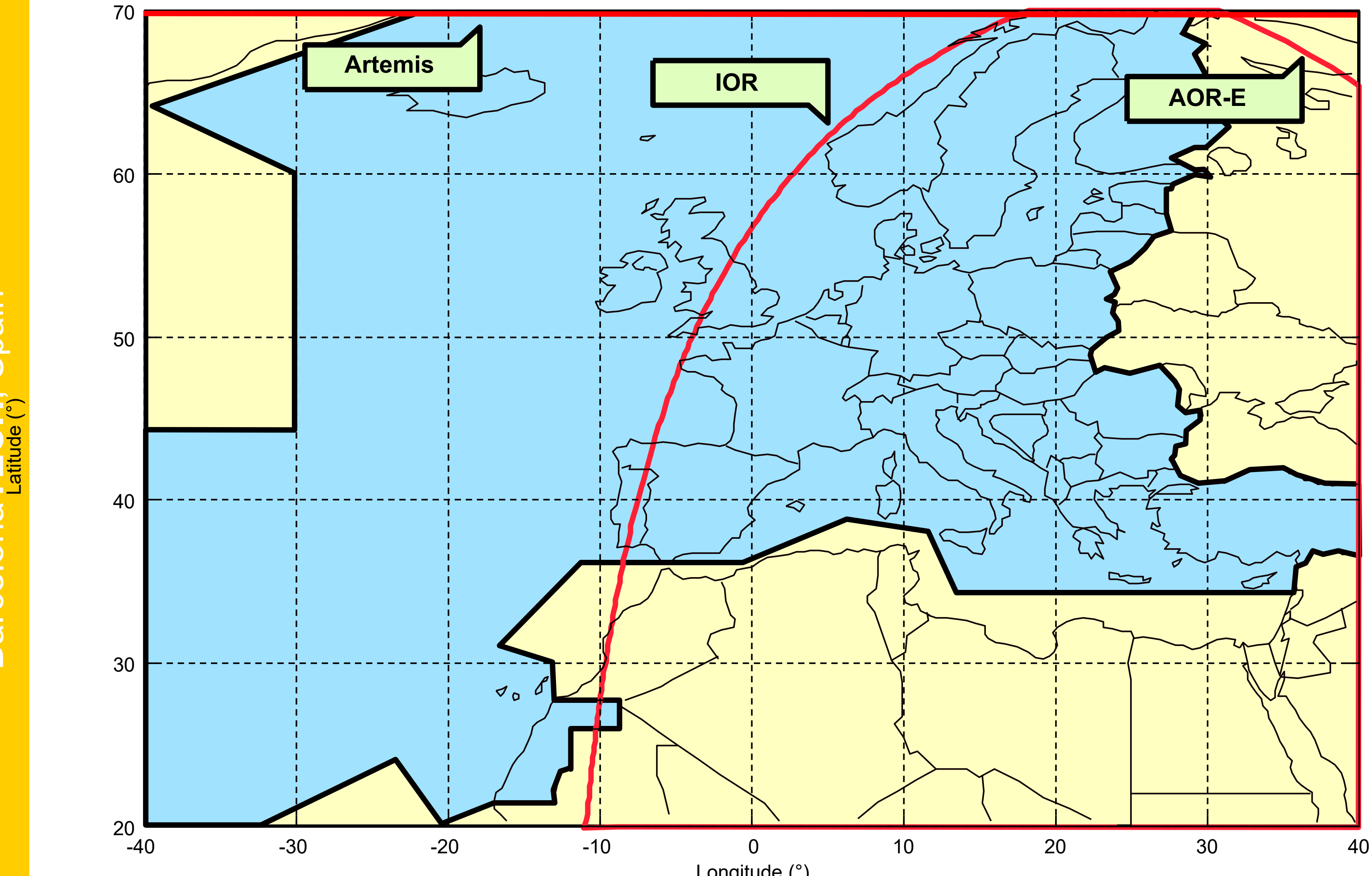
The European Geostationary Navigation Overlay SERVICE (EGNOS)

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

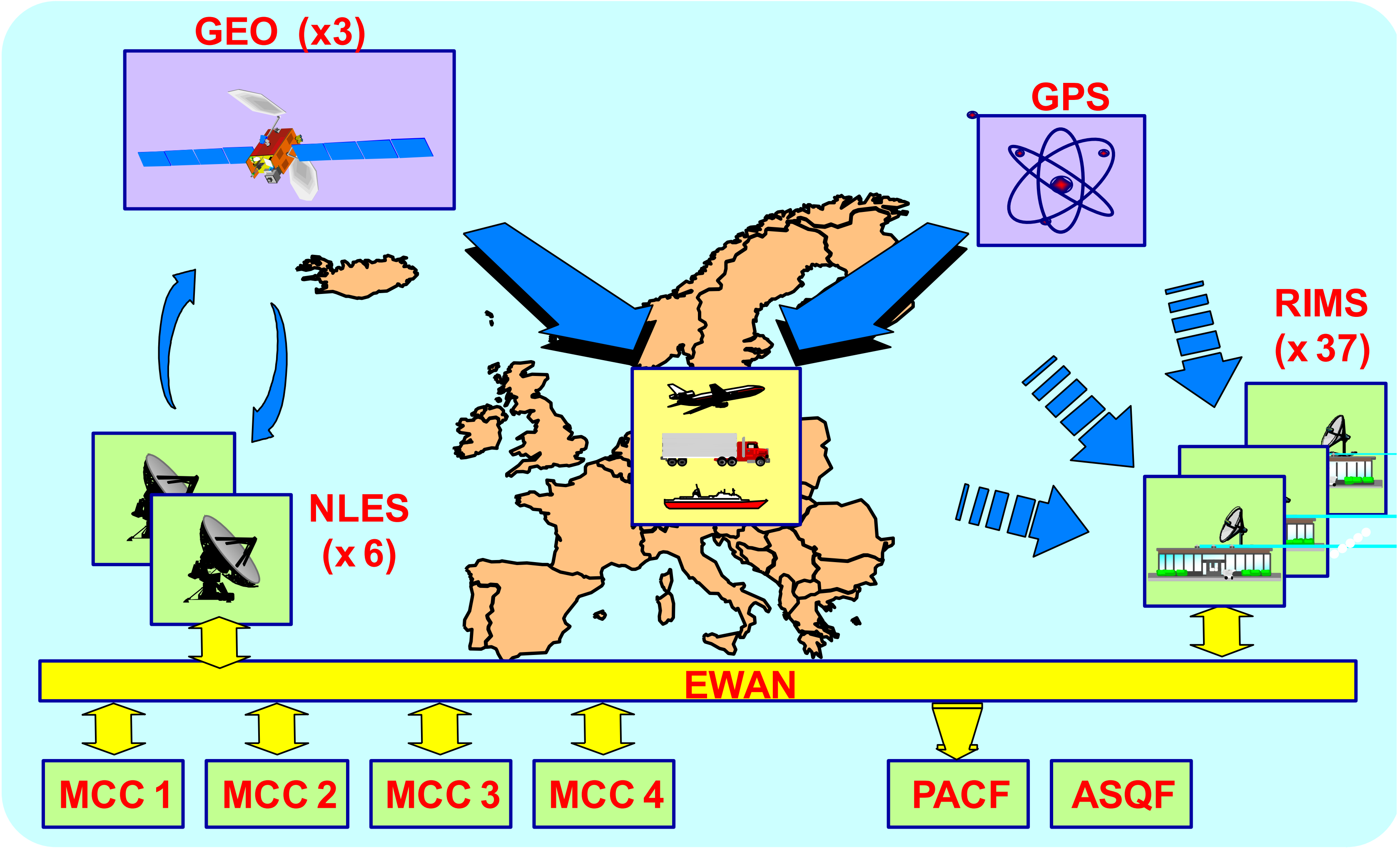
- EGNOS is being developed under the responsibility of a tripartite group:
  - The European Space Agency (ESA)
  - The European Organization for the Safety of Air Navigation (EUROCONTROL)
  - The Commission of the European Union

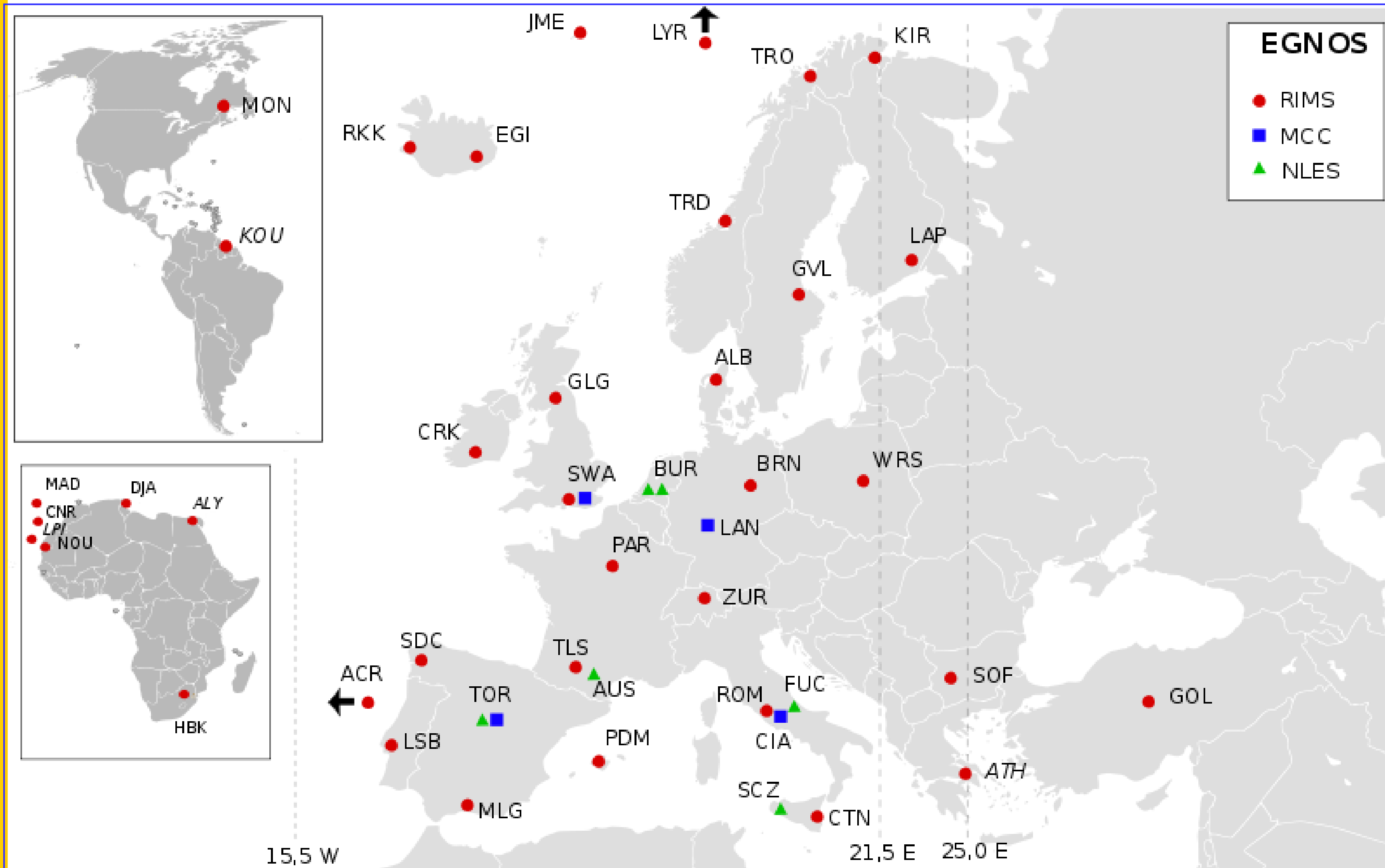
ECAC Area

(ECAC: European Civil Aviation Conference)



EGNOS Architecture




EGNOS
RIMS
MCC
NLES
MON
KOU
MAD
DJA
CNR
LPI
NOU
ALY
HBK
JME
LYR
TRO
KIR
RKK
EGI
TRD
LAP
GVL
ALB
GLG
CRK
SWA
BUR
BRN
WRS
LAN
PAR
ZUR
SDC
TLS
ACR
TOR
AUS
ROM
FUC
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CIA
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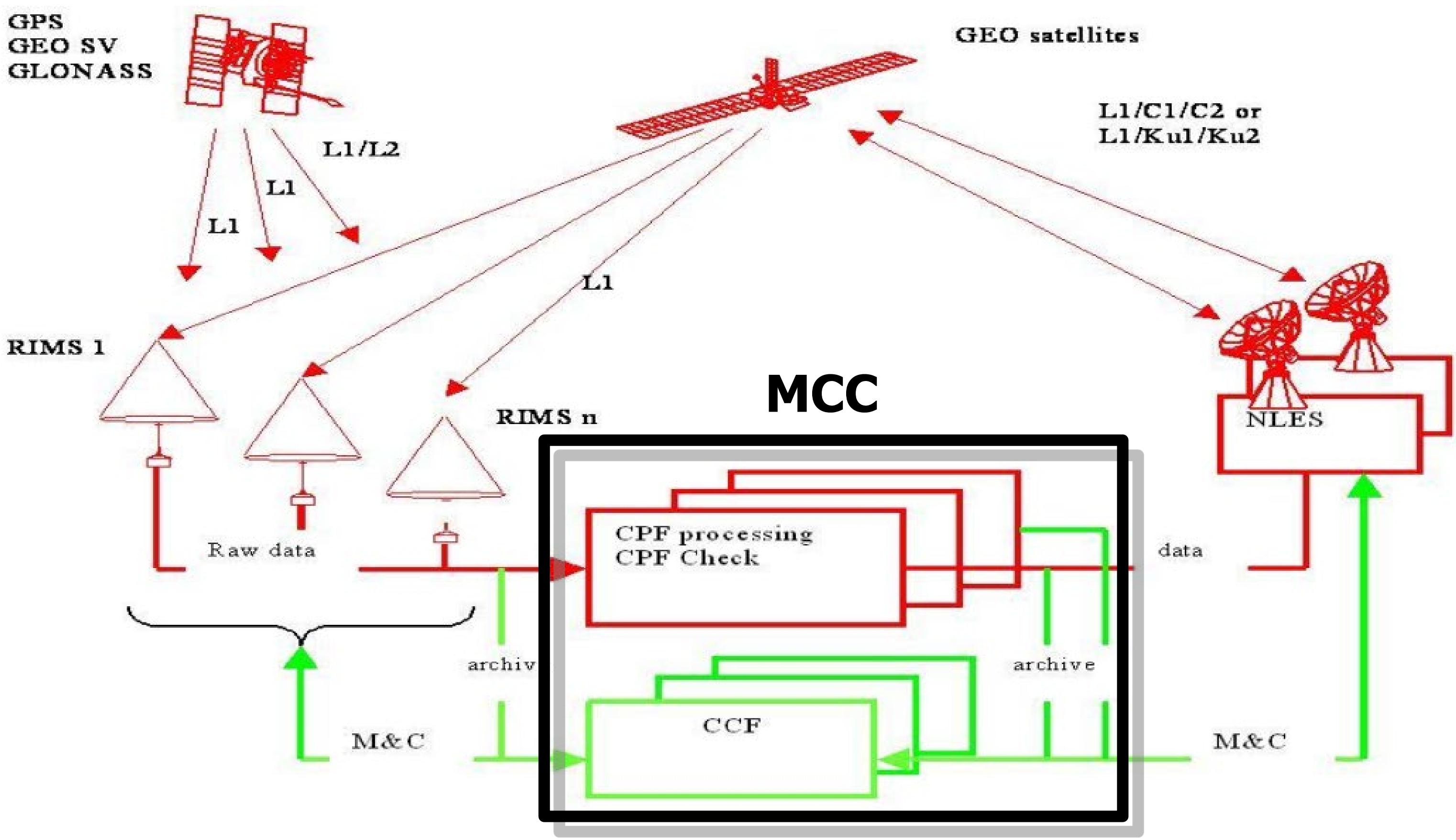
15,5 W
21,5 E
25,0 E

EGNOS DATA FLOW



Source: Javier Ventura-Traveset.

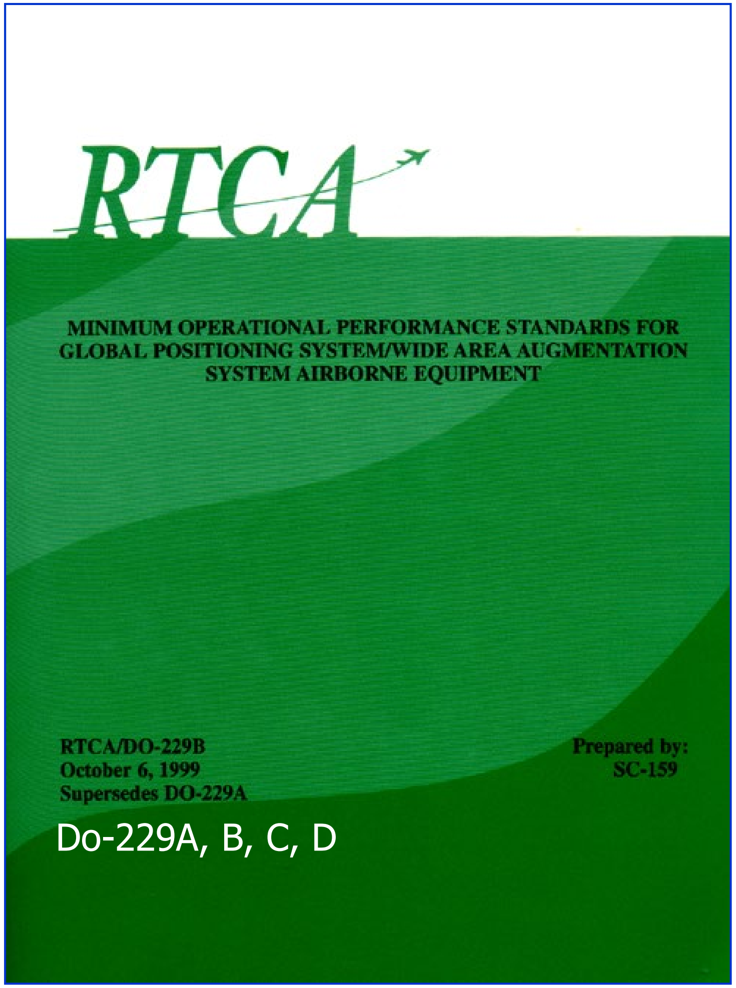
EGNOS ground segment is composed of the following stations/centres which are mainly distributed in Europe and are interconnected between themselves **through a land network**.

- **37 RIMS** (Ranging and Integrity Monitoring Stations) + seven being deployed: receive the satellite signals and send this information to the MCC centres. **The RIMS are the 'eyes' of EGNOS**
- **4 MCC** (Master Control Centres) receive the information from the RIMS stations and generate correction messages to improve satellite signal accuracy and information messages on the status of the satellites (integrity). **The MCC acts as the EGNOS system 'brain'.**
- **6 NLES** (Navigation Land Earth Stations): they receive the correction messages from the CPFs for the upload of the data stream to the geostationary satellites and the generation of the GPS-like signal. This data is then transmitted to the European users via the geostationary Satellite. **The NLES are the 'mouth' of EGNOS.**

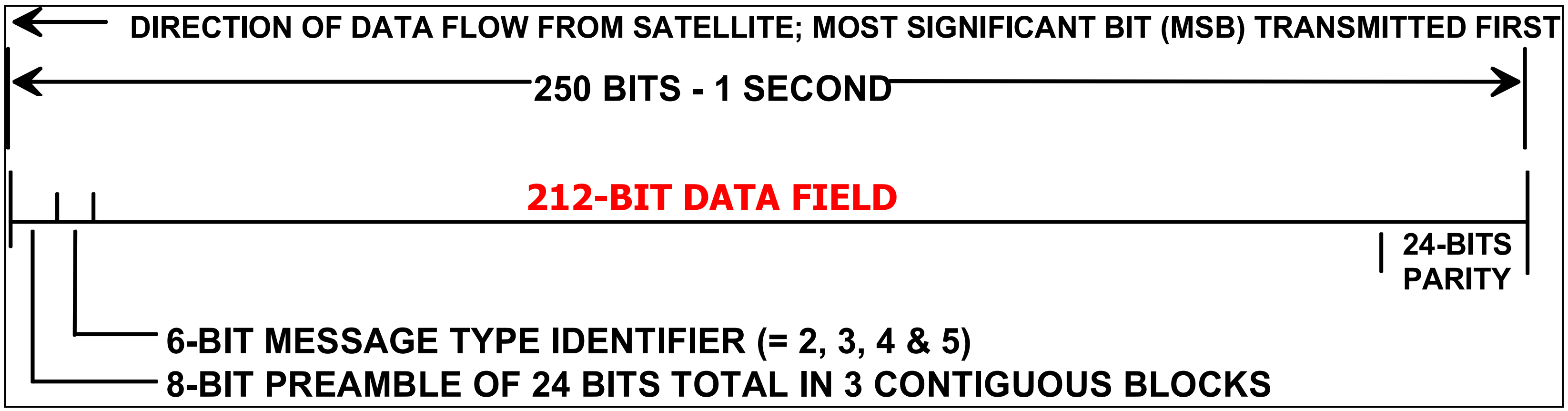
http://egnos-user-support.essp-sas.eu/egnos_ops/egnos_system/system_description/current_architecture

SBAS Differential Corrections and Integrity:

The RTCA/MOPS-DO 229C



Message Format



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

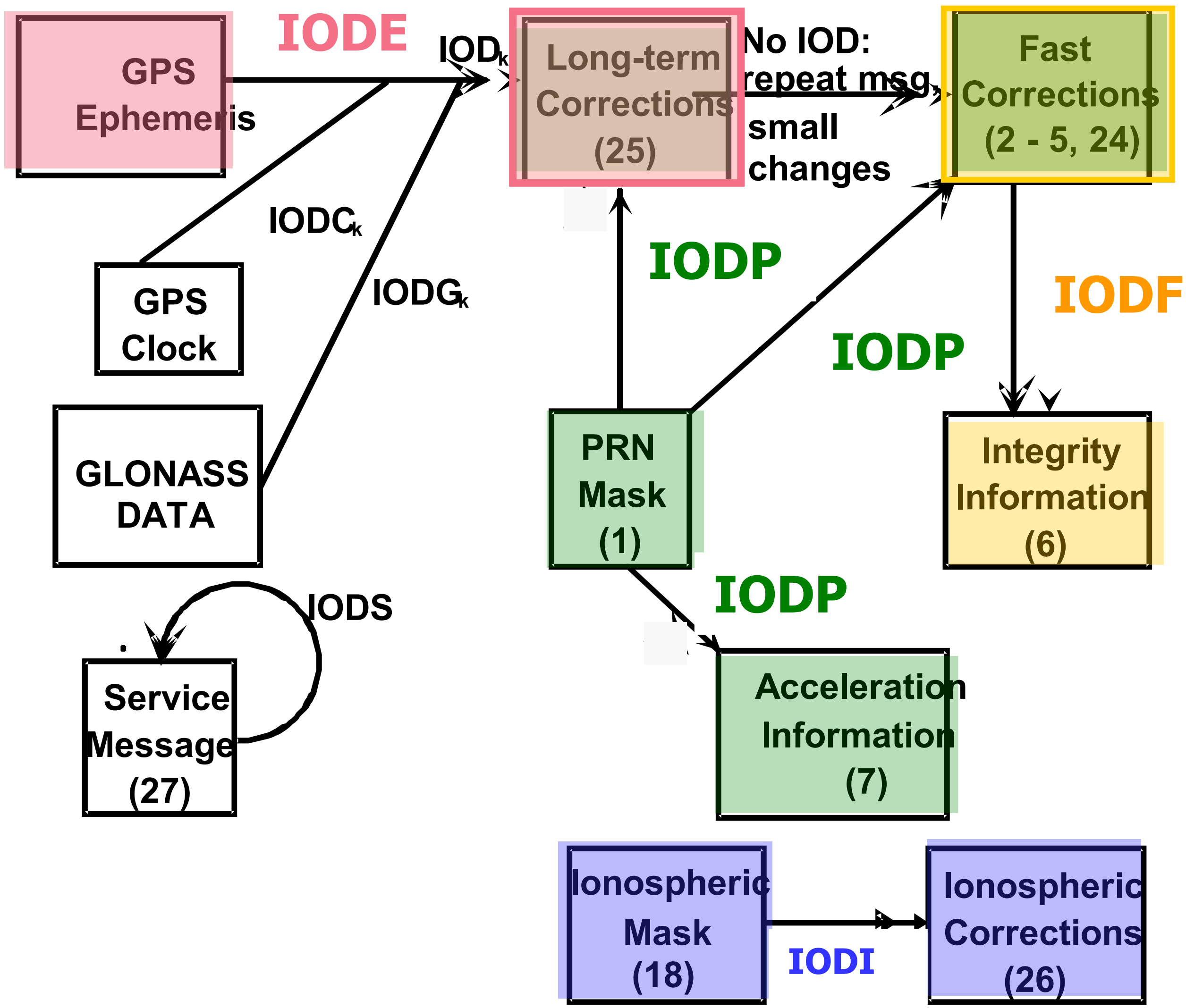
- 250 bits
- One Message per second
- All messages have identical format

SBAS 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)

Issues of Data (IOD)



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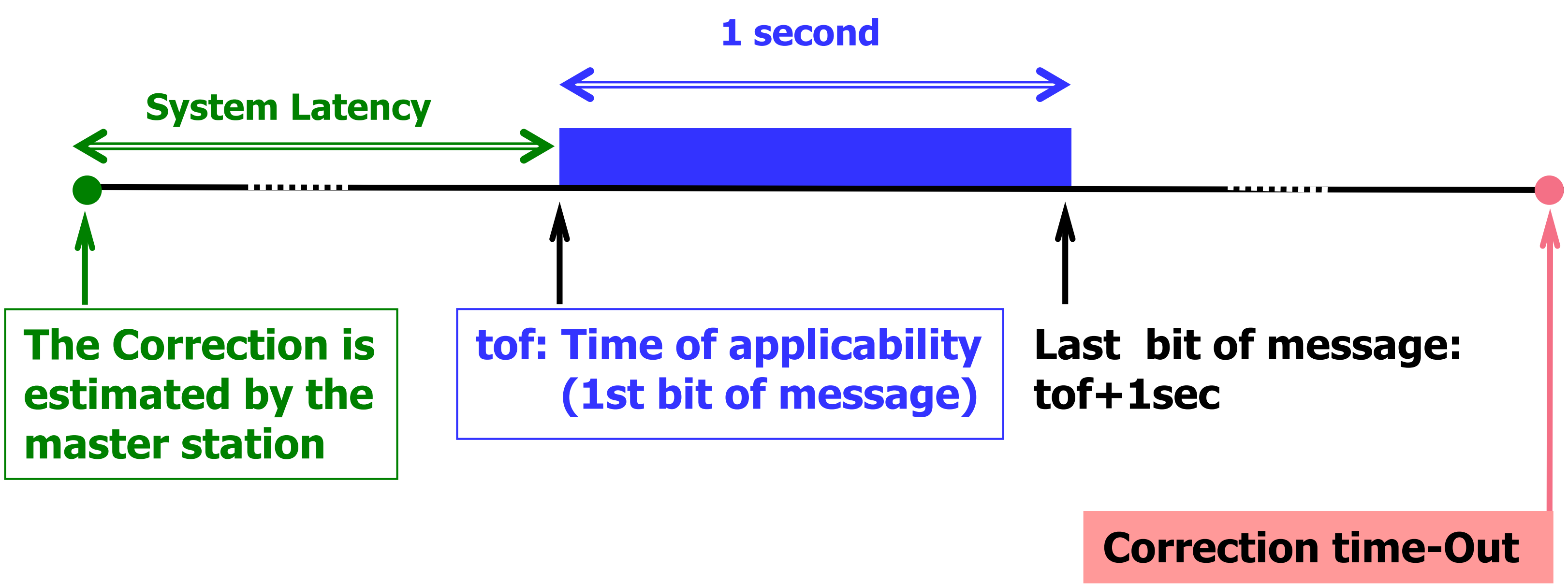
Message Time-Outs:

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]

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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

Example of message: Fast Corrections (MT2-5,24)

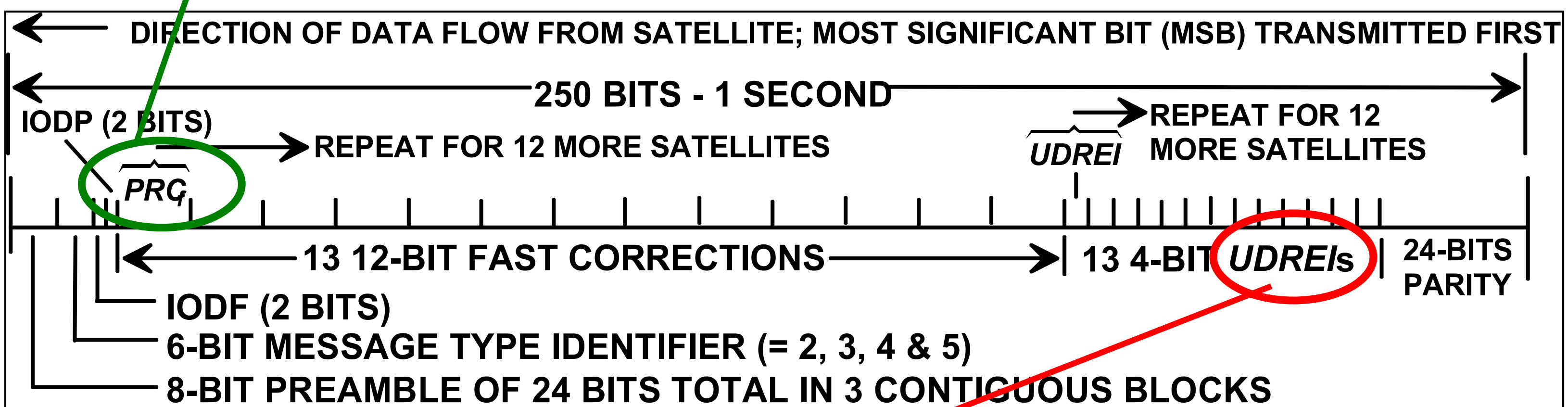
- Primarily Removed SA
  - Common to ALL users
  - Up to 13 Satellites Per Message
  - Pseudorange Correction /confidence Bound
  - Range Rate Formed by Differencing
  - UDRE degrades Over Time
    - Acceleration Term in MT 7
    - Reset when new Message Received

Example of message: Fast Corrections (MT2-5,24)

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

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

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



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

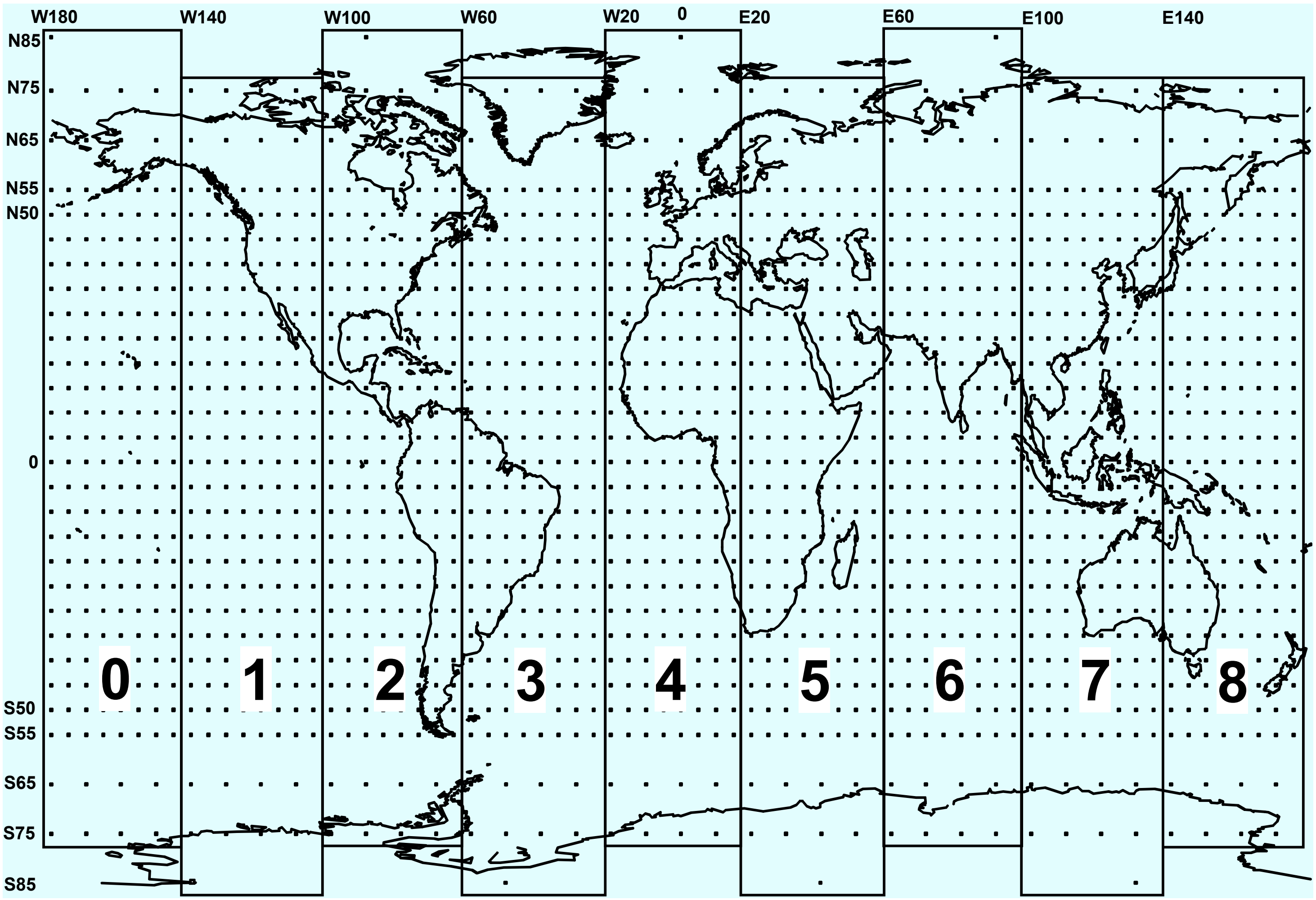
$$\sigma^2_{i,flt} = \sigma^2_{UDRE} + \varepsilon^2_{fc} + \varepsilon^2_{rrc} + \varepsilon^2_{ltc} + \varepsilon^2_{er}$$

Example of message: Ionospheric Corrections (MT26)

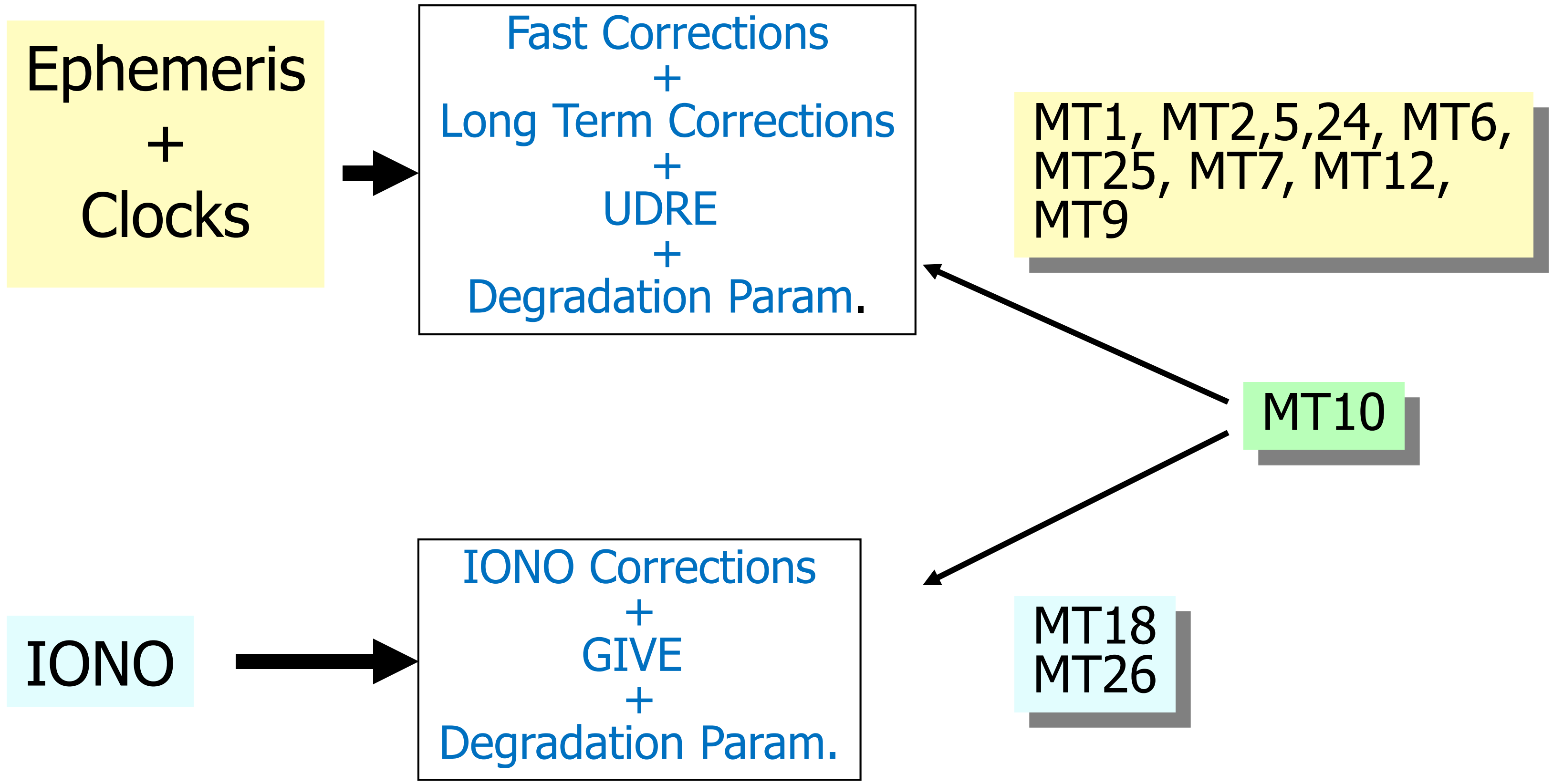
- Only Required for Precision Approach
  - Grid of Vertical Ionospheric Corrections
  - Users Select 3 o 4 IGPs surrounding the IPP
    - 5ºx5º or 10ºx10º for 55º<Lat<55º
    - Only 10ºx10º for 55º<|Lat|<85º
    - Circular regions for |Lat|>85º
  - Vertical Correction and UIVE Interpolated to IPP
  - Both Converted to Slant by Obliquity Factor

IGP: Ionospheric Grid Point
IPP: Ionospheric Pierce Point

Global IGP Grid



Predefined Global IGP Grid



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

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

Navigation System Error and Protection levels

$$\mathbf{y} = \mathbf{G} \cdot \mathbf{x}$$

$$\hat{\mathbf{x}} = \left(\mathbf{G}^T \mathbf{W} \mathbf{G}\right)^{-1} \mathbf{G}^T \mathbf{W}\, \mathbf{y}$$

$$\mathbf{x} = \left[\Delta N, \Delta E, \Delta U, cdt\right]$$

$$\mathbf{P}_{\mathbf{x}} = \left(\mathbf{G}^T \mathbf{W} \mathbf{G}\right)^{-1} = \begin{bmatrix} d_N^2 & d_{NE} & d_{NV} & d_{NT} \\ d_{NE} & d_E^2 & d_{EV} & d_{ET} \\ d_{NV} & d_{EV} & d_V^2 & d_{VT} \\ d_{NT} & d_{ET} & d_{VT} & d_T^2 \end{bmatrix}$$

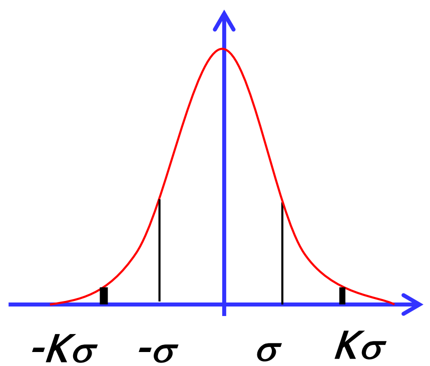
$$HPL = 6.00\sqrt{\frac{d_N^2 + d_E^2}{2} + \sqrt{\left(\frac{d_N^2 - d_E^2}{2}\right)^2 + d_{NE}^2}}$$

$$\mathbf{W} = \mathbf{P}_y^{-1}$$

$$VPL = 5.33\, d_V$$

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

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



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

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

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Fast and Long-Term Correction Degradation

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

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

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

$(when\ IODF \neq 3)$

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

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

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

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

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

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

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

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

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

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

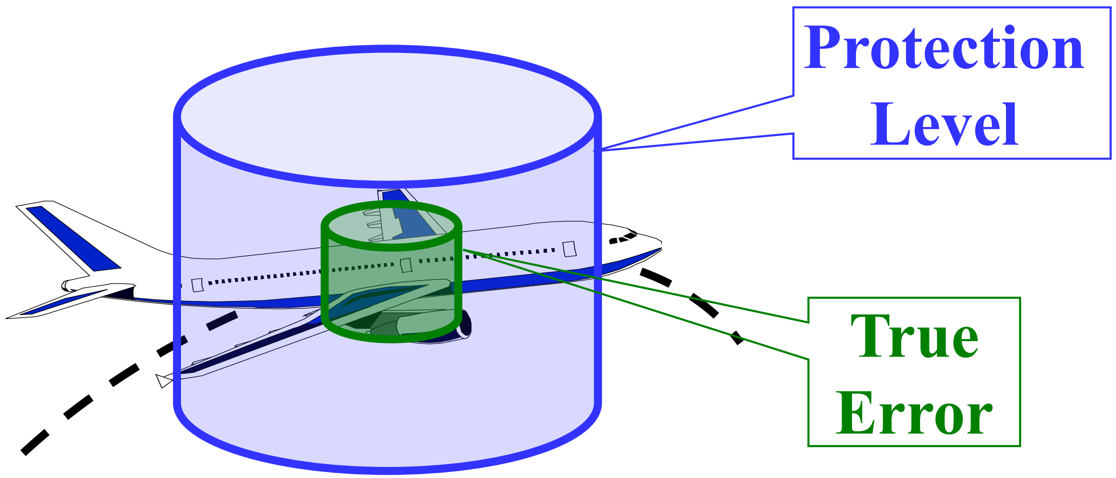
MT10

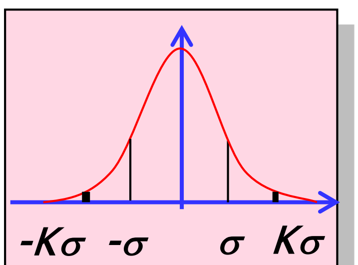
$B_{rrc}, C_{ltc\_lsb}, C_{ltc\_v1}, I_{ltc\_v1}, C_{ltc\_v0}, I_{ltc\_v0}, C_{er}, RSS_{UDRE}, C_{iono\_ramp}, C_{iono\_step}, I_{iono}, RSS_{iono}$

MT26

$t_{iono}, GIVE_i$

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

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

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

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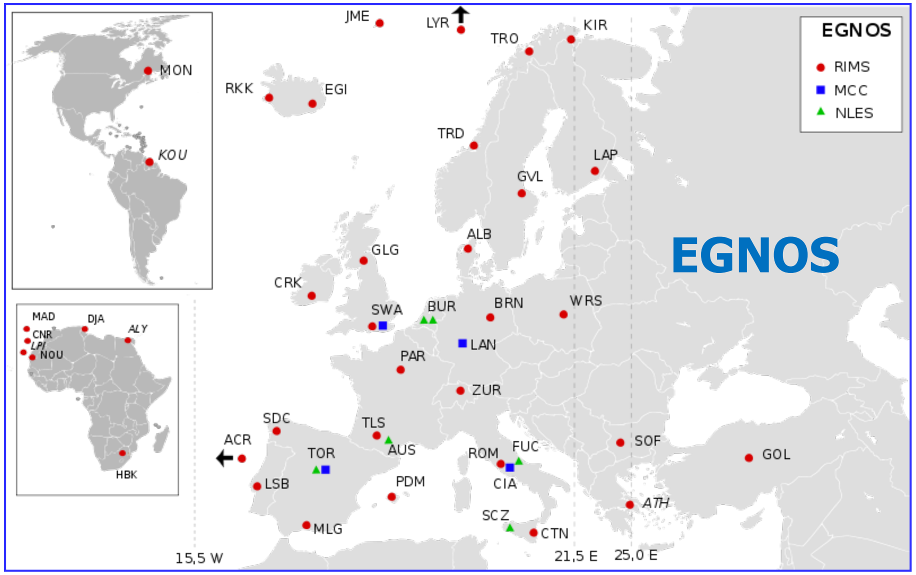

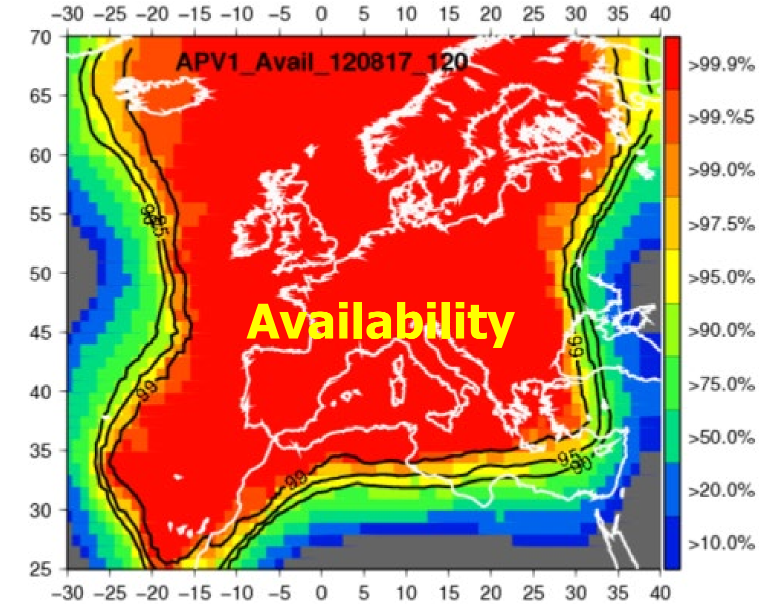

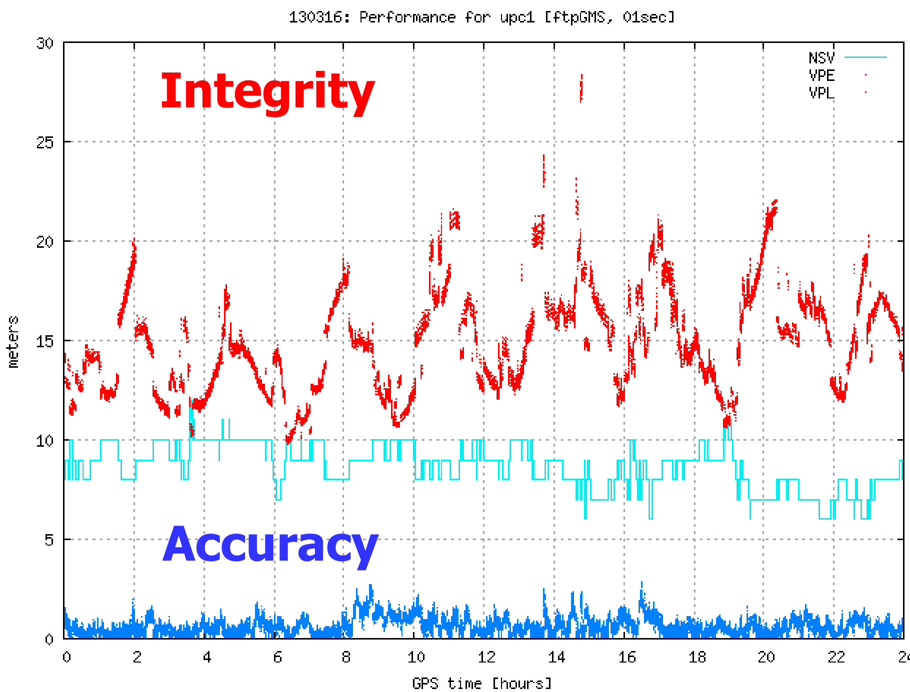

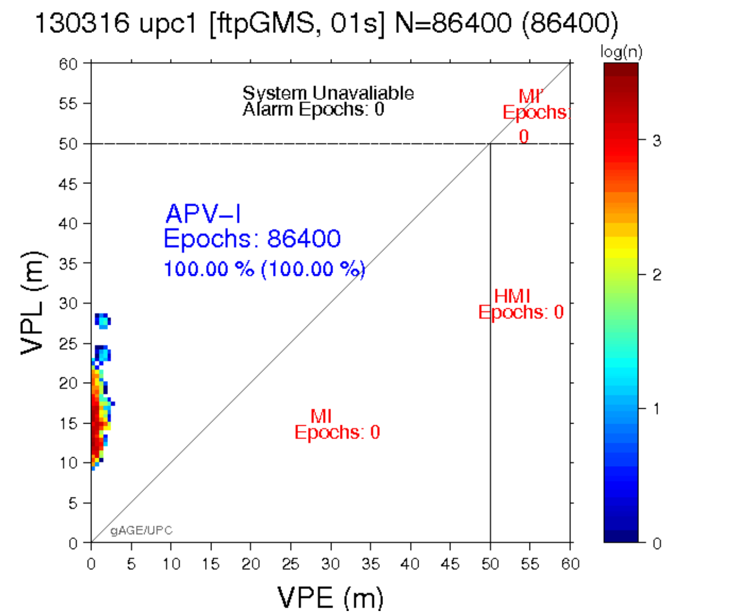

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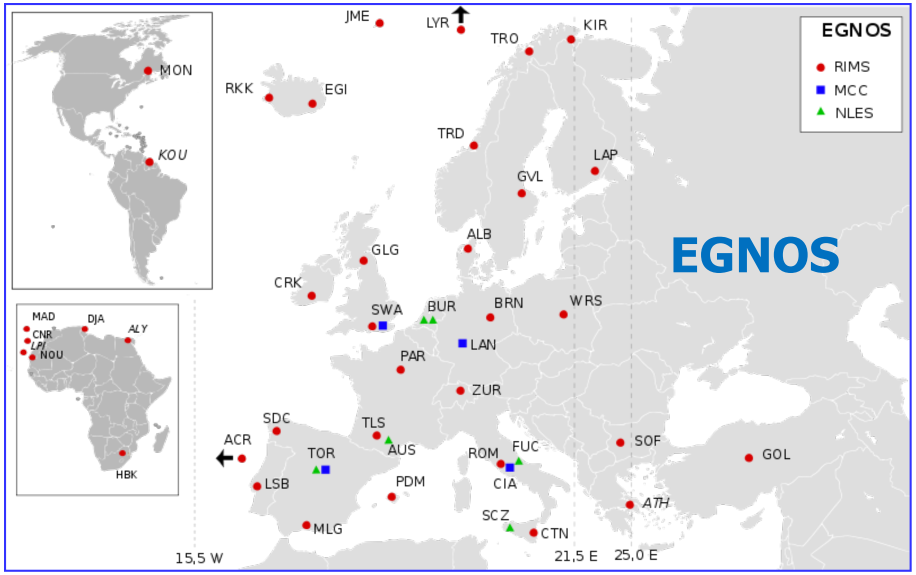

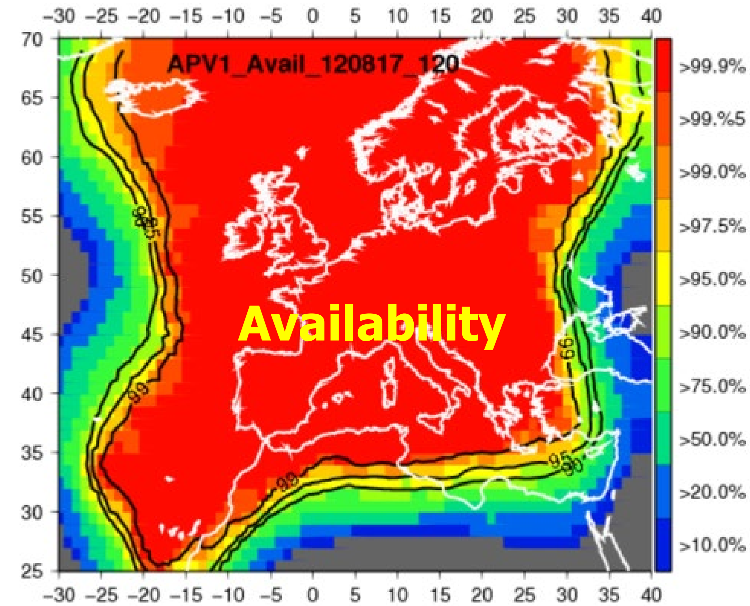

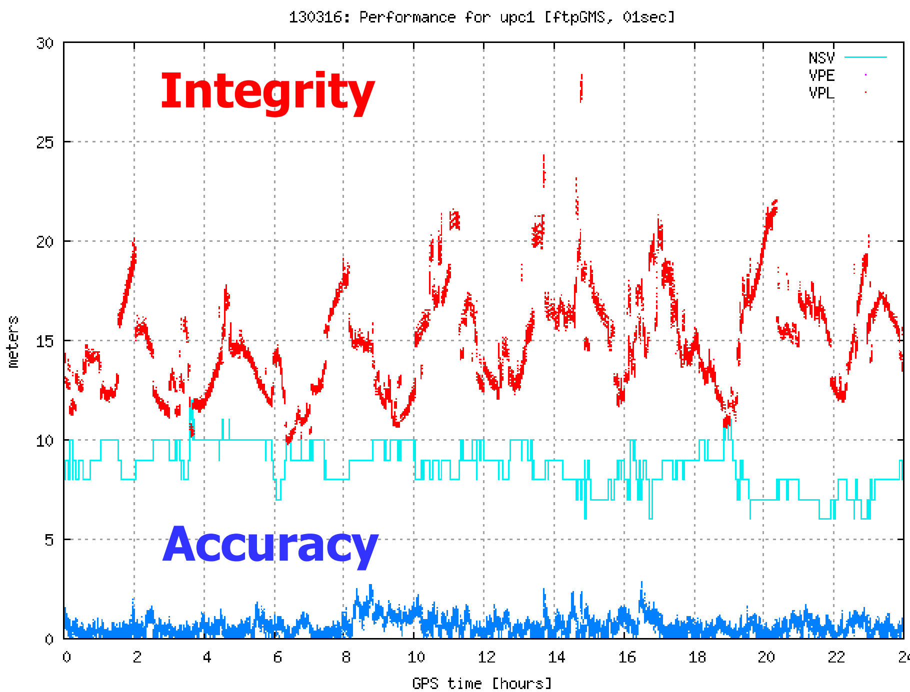

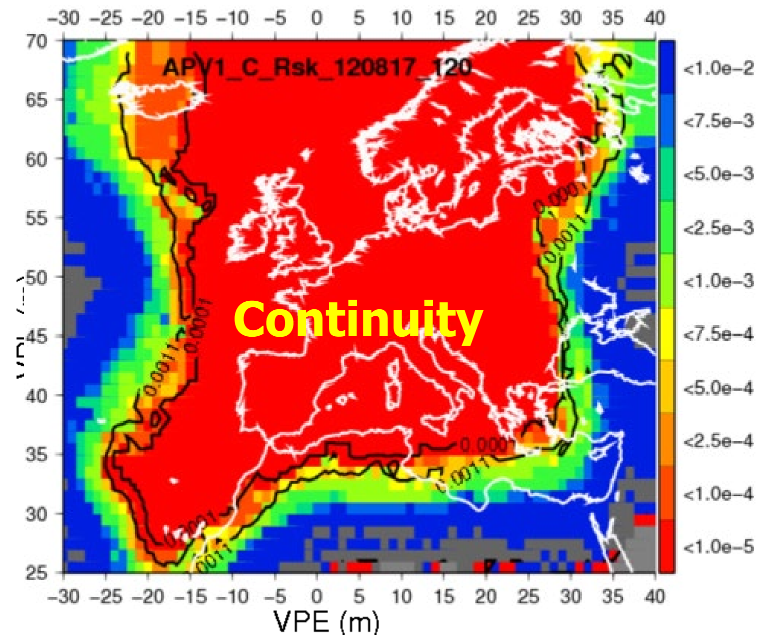

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EGNOS PERFORMANCES - Accuracy

EGNOS Measured Accuracies (Average Value 21-27 April 2010) over 24h

Place	MLG	SDC	PDM	LSB	TRD	CRK	ZUR	BRN	TLS	TRO	LAP
HNE (95%)	0.94	1.05	0.76	0.96	0.6	0.8	0.94	0.89	0.84	1.06	0.78
VNE (95%)	1.08	0.92	0.98	1.59	1.03	1.35	0.99	1.07	0.99	2.17	1.68

Place	SWA	ROM	ALB	GLG	KIR	GVL	WRS	CTN	CNR
HNE (95%)	1.12	0.79	0.65	0.65	0.89	0.58	1.13	1.02	1.33
VNE (95%)	1.62	1.12	1.3	1.37	1.84	1.52	1.25	1.05	1.72

HNSE (95%) 0.8-1.15m & VNSE (95%) around 0.9 -1.6 m

To be noted:

Less than 1 m horizontal accuracies recorded in EGNOS quite often;

Excellent vertical accuracies 1-2m (well below the 7.6 m specification)

Source: Javier Ventura-Traveset.
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GPS INTEGRITY FAILURES
EXAMPLE: PRN 23 ANOMALY ON JAN. 1, 2004

- GPS Block II-A-10 Satellite SVN-23 Suffered an Integrity Failure on 01 Jan 04
  - Operating on a Rubidium clock
  - Clock failed at about 18:30 UTC (Holiday Afternoon)
  - Clock failure caused a substantial frequency error
  - An integrity failure because no timely warning issued

- GPS Operations Set SVN-23 Unhealthy at about 21:18 UTC (i.e after 2h and 48 minutes)
  - Accumulated pseudorange error was about 285,000 m
  - SVN-23 remained trackable as PRN-23 until it was declared unhealthy

Source: Javier Ventura-Traveset.

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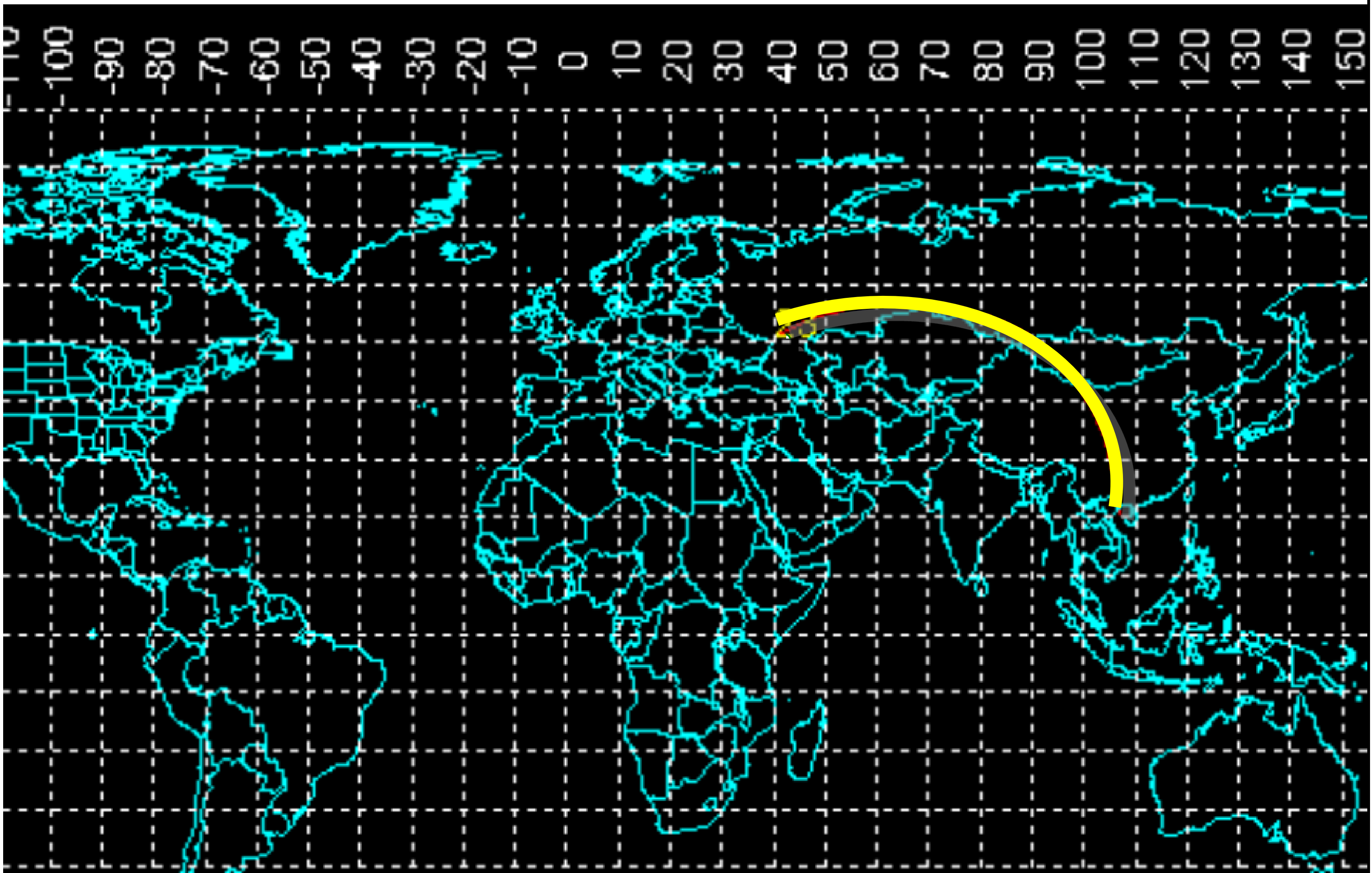
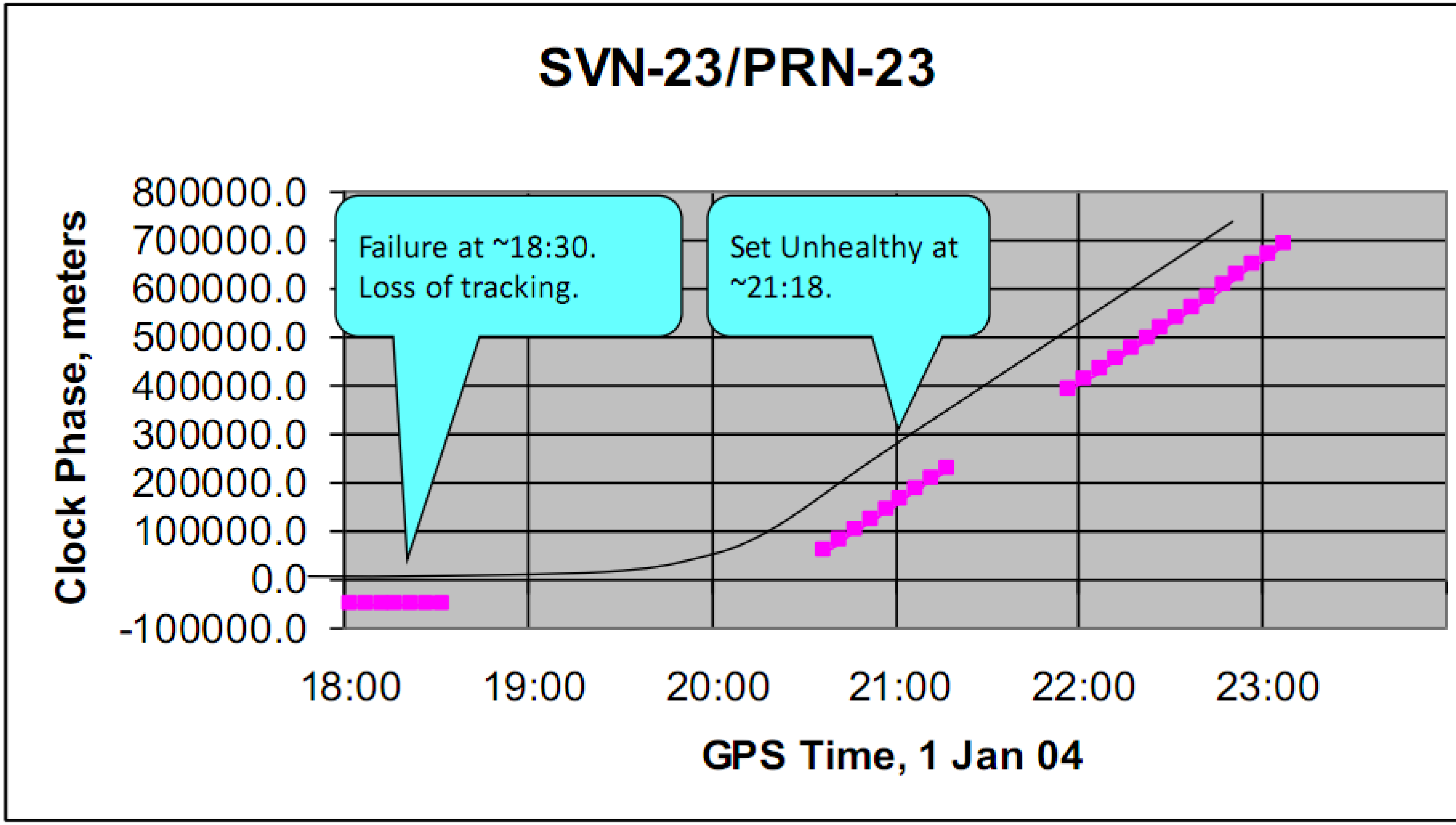
EXAMPLE: GPS PRN 23 ANOMALY ON JAN. 1, 2004



EXAMPLE: SV-23 CLOCK ERROR ON JAN 1, 2004



Source: Javier Ventura-Traveset.

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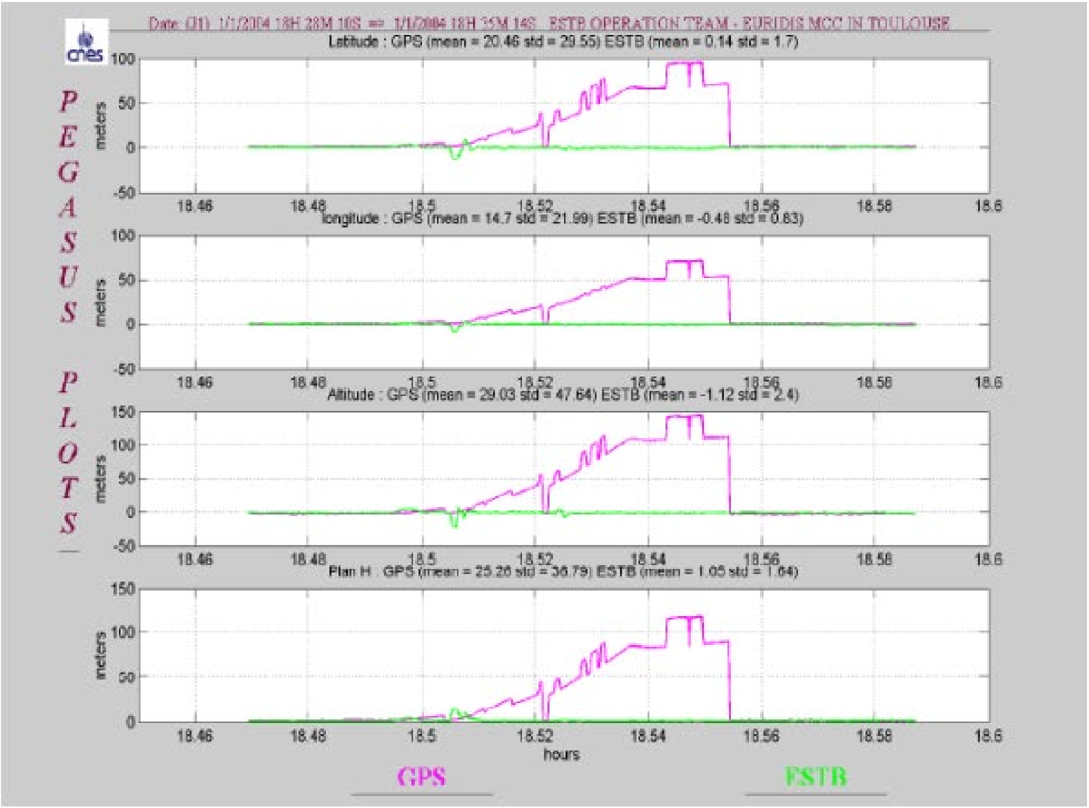
EXAMPLE: SV-23 CLOCK ERROR ON JAN 1, 2004

(Source CNES)



EGNOS integrity is effective discarding (on-time) the faulty satellite from the user solution. EGNOS accuracy is maintained in the 1-2 metres range

Source: Javier Ventura-Traveset.

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References

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[RD-2] J. Sanz Subirana, J.M. Juan Zornoza, M. Hernández-Pajares, GNSS Data processing. Volume 1: Fundamentals and Algorithms. ESA TM-23/1. ESA Communications, 2013.

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[RD-4] Pratap Misra, Per Enge. Global Positioning System. Signals, Measurements, and Performance. Ganga-Jamuna Press, 2004.

[RD-5] Gang Xie, Optimal on-airport monitoring of the integrity of GPS-based landing systems, PhD Dissertation, 2004.

[RD-6] B. Hofmann-Wellenhof et al. GPS, Theory and Practice. Springer-Verlag. Wien, New York, 1994.

[RD-7] ESA/JRC International Summer School on GNSS 2015. Presentations Booklet. Barcelona, Spain. August 31st to September 10th 2015.

Thank you

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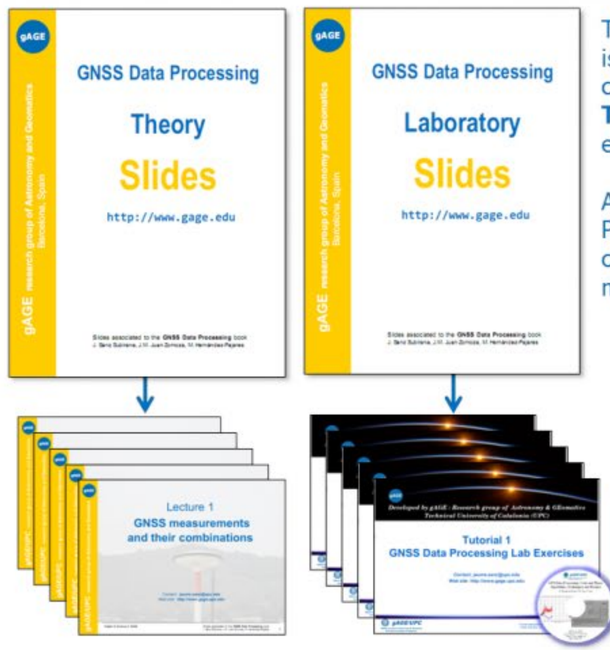

The Learning material is composed by a collection of slides for **Theory** & **Laboratory** exercises.

A book on GNSS Data Processing is given as complementary material.

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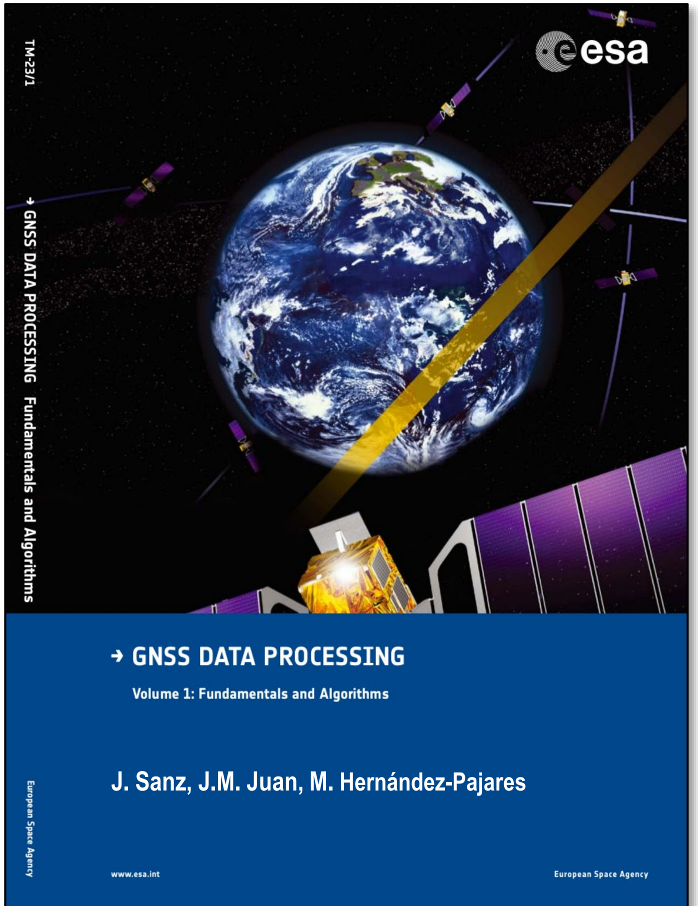

GNSS Data Processing, **Vol. 1: Fundamentals and Algorithms.**
GNSS Data Processing, **Vol. 2: Laboratory exercises.**

Backup Slides

EGNOS Safety of Life Service Definition Document (Ref : EGN-SDD SoL, V1.0). **European Comission**.

http://www.essp-sas.eu/downloads/vubjj/egnos_sol_sdd_in_force.pdf

Error sources (1σ)	GPS - Error Size (m)	EGNOS - Error Size (m)
GPS SREW	4.0[12]	2.3
Ionosphere (UIVD error)	2.0 to 5.0[13]	0.5
Troposphere (vertical)	*0.1*	*0.1*
GPS Receiver noise	*0.5*	*0.5*
GPS Multipath (45º elevation)	*0.2*	*0.2*
GPS UERE 5º elevation	**7.4 to 15.6**	**4.2 (after EGNOS corrections)**
GPS UERE 90º elevation	**4.5 to 6.4**	**2.4 (after EGNOS corrections)**

[12] *GPS Standard Positioning Service Performance Standard [RD-3].*
[13] *This is the typical range of ionospheric residual errors after application of the baseline Klobuchar model broadcast by GPS for mid-latitude regions.*

SREW: Satellite Residual Error for the Worst user location.
UIVD: User Ionospheric Vertical Delay.
UERE: User Equivalent Range Error

SQM: Targets satellite signals anomalies and local interference. Implements tests for Correlation Peak Symmetry, Receiver Signal Power and Code-Carrier Divergence.

DQM: Checks the validity of the GPS ephemeris and clock data for each satellite that rises in view of the LGF and at each time new navigation data messages are broadcast.

MQM: Confirms the consistency of the pseudorange and carrier-phase measurements over the last few epochs to detect sudden step and any other rapid errors.

MRCC: Examines the consistency of corrections for each satellite across all reference receivers.

σμ-monitor: Helps ensure a Gaussian distribution for the correction error with zero mean and that the broadcast σ_{pr_gnd} overbounds the actual errors in the broadcast differential corrections.

MFRT: Verifies that the computed averaged pseudorange corrections and correction rates fit within the message field bounds.

This is from [RD-5]

Executive Monitors (EXM-I and EXM-II) coordinate all previous monitors and combine failure flags.

- Signal Quality Monitoring (SQM)
- Data Quality Monitoring (DQM)
- Measur. Quality Monitoring (MQM)
- Multiple Reference Consist Check (MRCC)
- σμ-monitor
- Message Field Range Test (MFRT)

Civil 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