Seamless GNSS through integrated user equipment:

A joint evaluation of US and EU systems

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UNITED NATIONS
Office for Outer Space Affairs

EU-US GNSS Cooperation in WG-C

- On 29 July 2010, the Government of the United States, the European Union (EU) and its Member States announced the conclusion of an initial phase of consultations affirming user interoperability and enhanced performance of combined GPS and Galileo receivers performance under the auspices of their
  - 2004 *Agreement on the Promotion, Provision and Use of Galileo and GPS Satellite-Based Navigation Systems and Related Applications*
- U.S./EU GPS-Galileo Agreement established Working Group C as "to promote cooperation on design and development of next generation of civil satellite-based navigation and timing systems"

WG-C Terms of Reference

WG-C terms of reference included:

- GPS/Galileo Receiver Integration and Performance Description
  - Phase A: Civil applications (excluding safety-of-life)
  - Deliverable: Joint document describing combined system performance for typical civil receivers
- Combined SBAS Performance Description
  - Phase A: SBAS performance for Safety-of-life
  - Deliverable: Joint document describing combined system performance for SBAS civil receivers

Background

- Subgroup established in Mar 2009 to evaluate GPS/Galileo combined performance for common open civil services
- Subgroup also established in Mar 2009 to evaluate SBAS combined performance
    - Ensure interoperability amongst WAAS and EGNOS
    - Compare performance between SBAS and GPS user equipment

WG-C Papers on Combined Performances

EU-US Cooperation on Satellite Navigation

Working Group C

COMBINED PERFORMANCES FOR OPEN GPS/GALILEO RECEIVERS

Final version

July 19, 2010

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EU-US Cooperation on Satellite Navigation

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COMBINED PERFORMANCES FOR SBAS RECEIVERS USING WAAS and EGNOS

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Combined GNSS Performances

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Combined GNSS Performances

Overall Objectives:

- Assess performance of future GPS and Galileo services by showing the performance of combined GPS III and Galileo open civilian signals
  - L1C / E1 and L5 / E5A
- Compare GPS, Galileo, and GPS/Galileo combined performance for three receiver types using four study cases
- Serve as a precedent for subsequent analyses on combined performance of other systems and services
- Facilitate multilateral discussions in other forums

Combined GNSS performances

Content

- Receiver types
- Environmental assumptions:
  - Ionosphere
  - Troposphere
  - Multipath
  - Interference
- GPS/Galileo Assumptions
- Performance Metrics
- Study Cases
- Results

Receiver Types

- Three receiver types:
  - Single Frequency SF BOC(1,1)
  - Single Frequency SF MBOC
  - Dual Frequency DF

Receiver type	*Frequency Mode*	*Processed Signals*	*Modulations*	*Bands and Bandwidths*
SF BOC(1,1)	Single Frequency	GPS L1C, Galileo E1	BOC(1,1)	1575.42 MHz ± 2 MHz
SF MBOC	Single Frequency	GPS L1C, Galileo E1	MBOC	1575.42 MHz ± 7 MHz
DF	Dual Frequency	GPS L1C + L5, Galileo E1 + E5a	MBOC - BPSK-R(10)	1575.42 MHz ± 7 MHz 1176.45 MHz ± 10 MHz

Environmental Assumptions

- Three ionospheric activity periods considered: maximum, average, minimum. GPS's Klobuchar ionospheric correction model for SF receivers
- Tropospheric model representing state-of-art solutions already existing in receivers
- Two multipath models representing urban (Jahn) and open-sky (Mats-Brenner) environments
- No interference considered

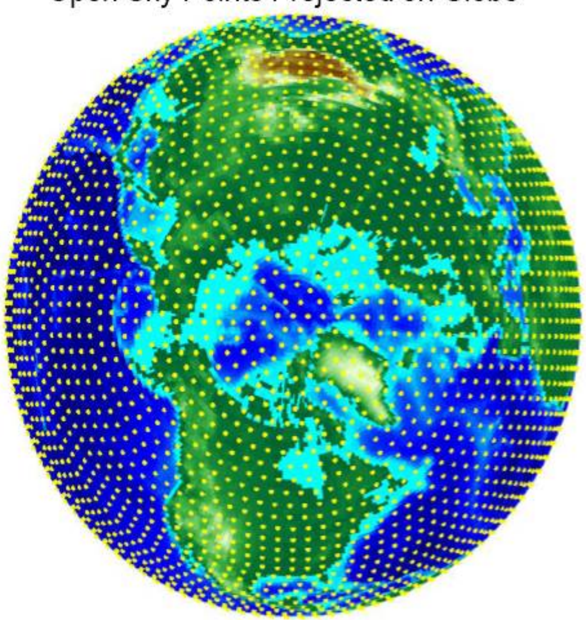
GPS/Galileo Assumptions

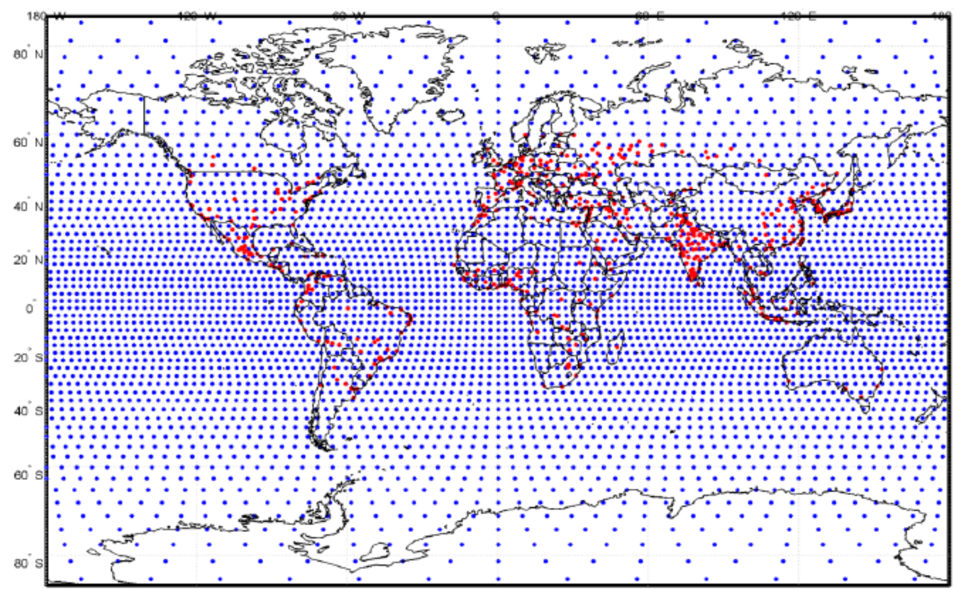
- Nominal constellations of 24 and 27 satellites for GPS and Galileo respectively
- Constellations synchronised as of Jul 1st 1993 00:00:00
- No satellite failures considered
- System synchronisation through GGTO

Performance Metrics

- VPE, HPE, Availability of accuracy
- User site determination:
  - Regular grid of equally distributed points
  - Urban points representing population exceeding one-half million or more

Open Sky Points Projected on Globe





Miller Projection: Blue = Open Sky; Red = Urban

Study Cases

- **Principal**: Effects on VPE and HPE arising from different constellations, environments, receivers, and solar cycle periods
- **Half-sky**: Effects on VPE and HPE in a partially occluded sky which eliminates satellites with azimuths between Zero and 180 degrees. The average solar cycle period is considered in this case
- **Urban-Global 15º**: Effects on VPE and HPE with peak solar period and all sites in the world considered urban
- **Urban-Global 30º**: Effects on VPE and HPE masking out elevation angles lower than 30º

All study cases conducted for GPS, Galileo, GPS plus Galileo, and three receiver types

Study Cases

Study	Principal Study *Urban*	Principal Study *Open Sky*	Half-Sky	Urban Global 15º	Urban Global 30º
Ionospheric Activity	Maximum Average Minimum	Maximum Average Minimum	Average	Maximum	Maximum
Multipath model	Jahn	Mats Brenner	Mats Brenner	Jahn	Jahn
Receiver types studied	SF BOC(1,1) SF MBOC DF (WLS iono combination)	SF BOC(1,1) SF MBOC DF (iono-free combination)	SF BOC(1,1) SF MBOC DF (iono-free combination)	SF BOC(1,1) SF MBOC DF (WLS iono combination)	SF BOC(1,1) SF MBOC DF (WLS iono combination)

Sample Results: Principal

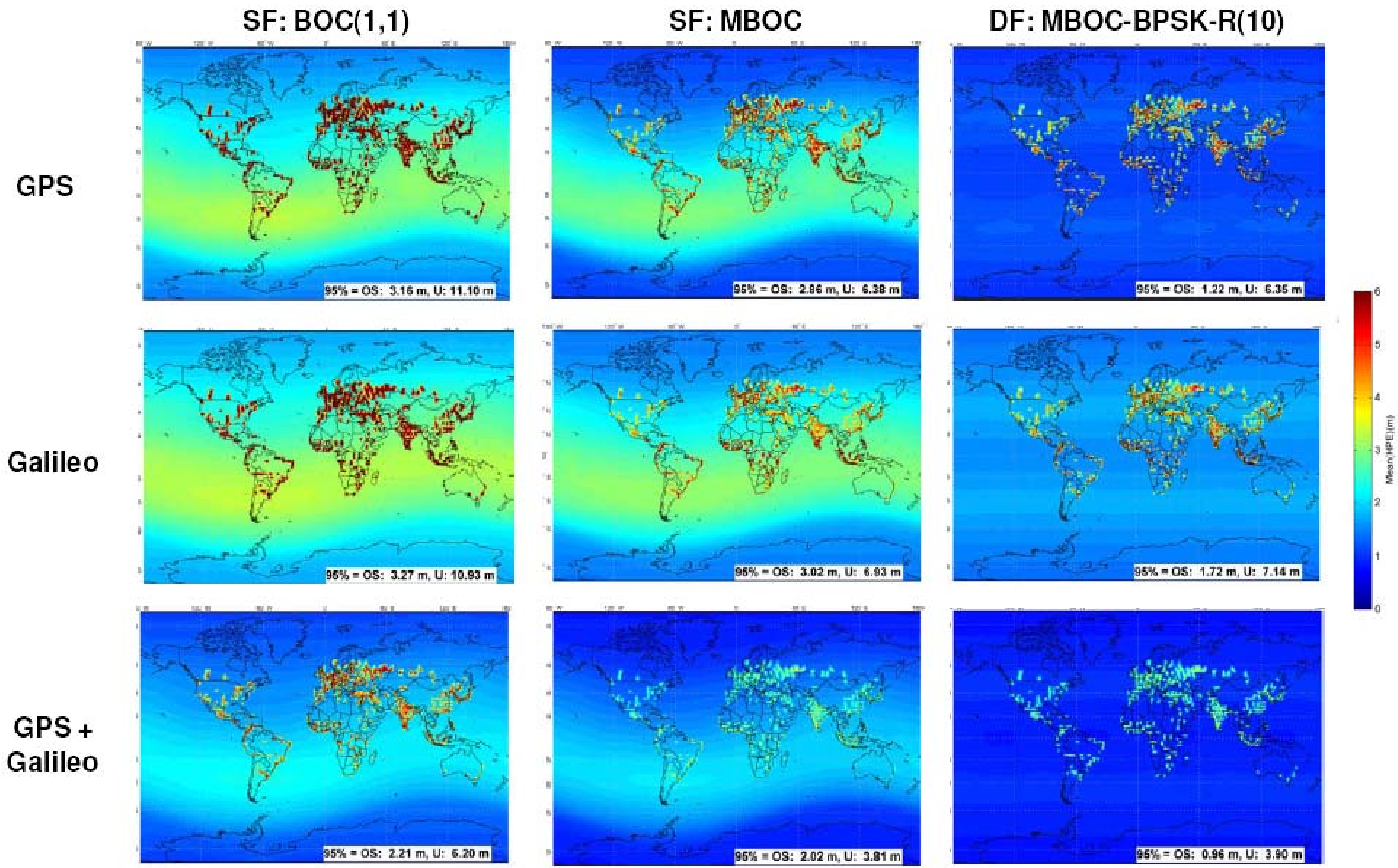


Figure 3-2: Principal Study - Comparison of Mean HPE(m) for Average Solar Cycle

Sample Results: Half-Sky

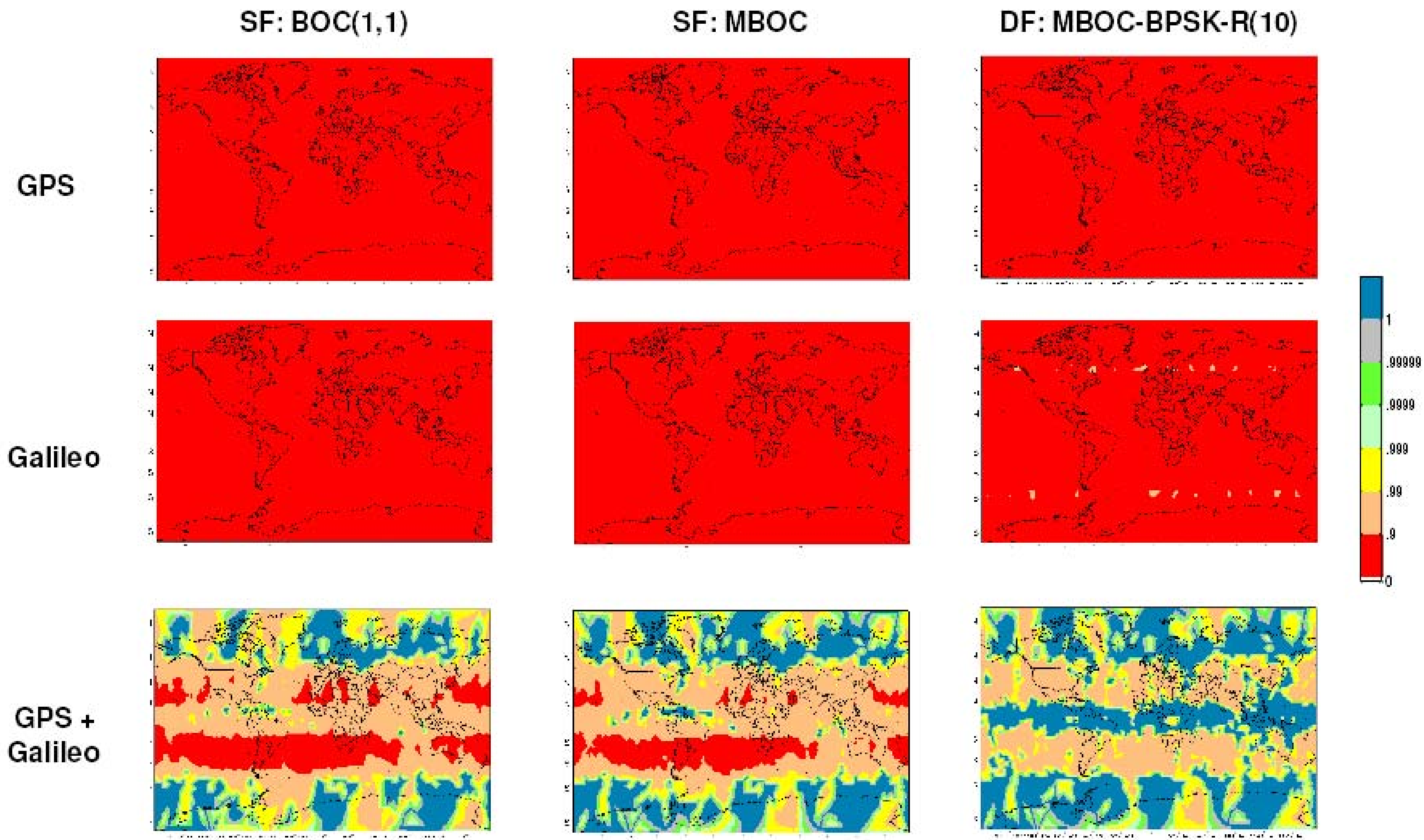


Figure 3-5: Half Sky Study - Availability of Accuracy (H=12m; V=14m); no satellite failure

Sample Results: Urban Global 15º

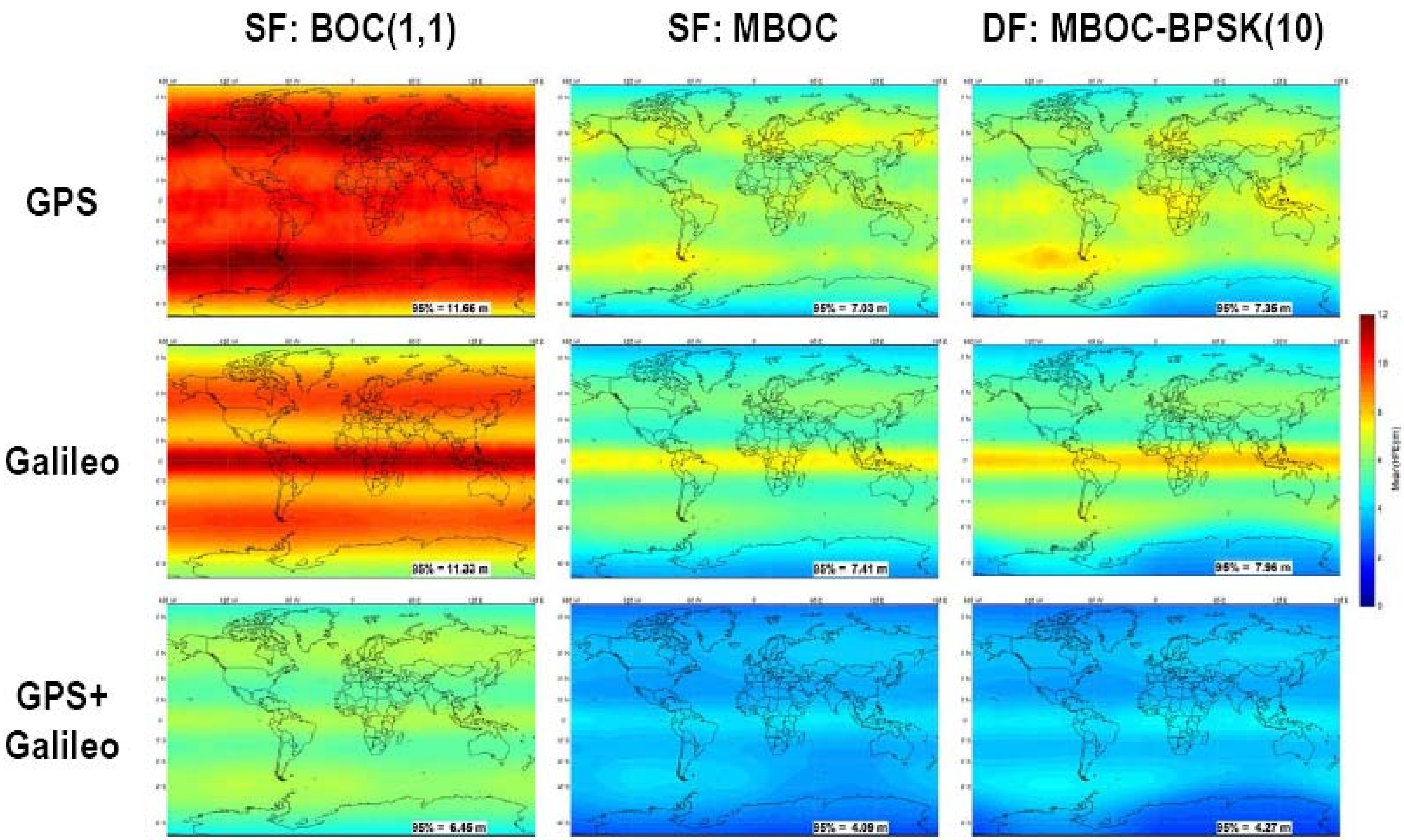


Figure 3-6: Urban Global Study (15°) -Comparison of Mean HPE(m) for Peak Solar Cycle

Additional Work Performed

- EU/US consolidated common performance analysis and simulation environment
- Validation of single frequency ionospheric error model
- Comparison of multipath models for urban/open sky
- Dual-frequency combination for high-multipath environments (WLS)

This technical note was prepared by the Working Group C with the MITRE Corporation and University FAF Munich as main contributors and with the participation of Stanford University and DLR. The technical activities leading to the results presented in this note were conducted by the MITRE Corporation and University FAF Munich.

Conclusions: Combined GNSS

- Combination of GPS and Galileo led to noteworthy performance improvements as compared to single system performance
- Most significant improvement is for partially obscured environments, where buildings, trees or terrain block portions of the sky.
- Dual-frequency receivers provide additional improvement over single-frequency in most environments
- Study illustrates benefits expected from future broadband signals on GPS and Galileo and other future GNSS systems

Combined SBAS Performances

EU-US Cooperation on Satellite Navigation

Working Group C

COMBINED PERFORMANCES FOR SBAS RECEIVERS USING WAAS and EGNOS

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Objective

- Assess global, combined performance for GPS Space-Based Augmentation System (SBAS) receivers
  - Using European Geostationary Navigation Overlay Service (EGNOS) and GPS Wide Area Augmentation System (WAAS)
  - For safety-of-life applications

Contents of Deliverable

- Overview of SBAS
  - Role of SBAS
  - Different SBAS systems and stage of development
- SBAS Interoperability and Architecture
  - Role of ICAO SARPs and Interoperability Working Group
  - How an SBAS augments GPS
- SBAS Services and Evolution
  - Focus is on aviation and all phases of flight
  - Defines service area
  - Evolution of SBAS and focus on incorporation on new civil signals and consideration of additional GNSS constellations

Contents of Deliverable (Continued)

- Performance Assessment
  - Provides both Receiver and System Assumptions
  - The assumptions included were specified by work efforts conducted in ICAO NSP
  - Comparison made between GPS/RAIM UE and SBAS/RAIM UE
    - Includes results from both a nominal 24 SV constellation and on that is degraded
    - Evaluation consisted of looking at various RNP levels
- Performance Results Summary

GPS and Current SBASs, 24-Satellite GPS Constellation, No Baro Aiding (GPS URA = 4 m)

GPS/RAIM UE

<u>SA OFF</u> Design

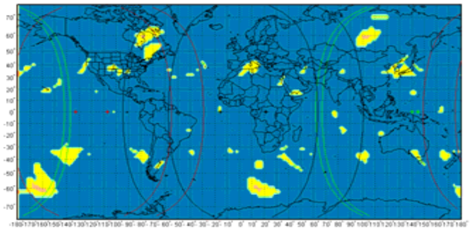
(TSO-C196)

<u>No Baro Aiding</u>

SBAS UE

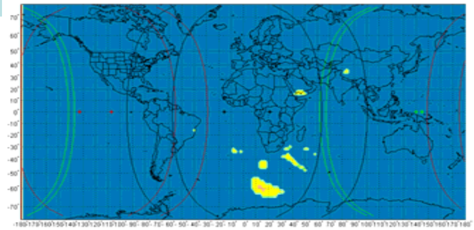
(TSO-C145/146)

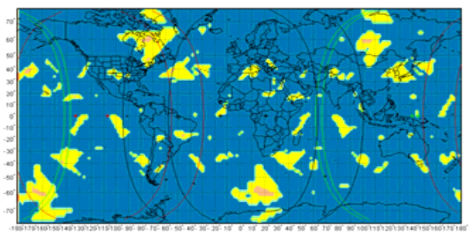
<u>No Baro Aiding</u>



HAL = 1.0 nm

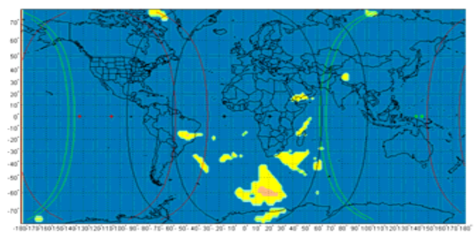
(RNP1.0)

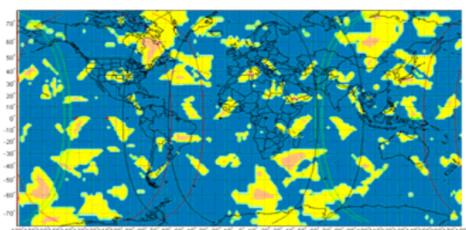




HAL = 0.5 nm

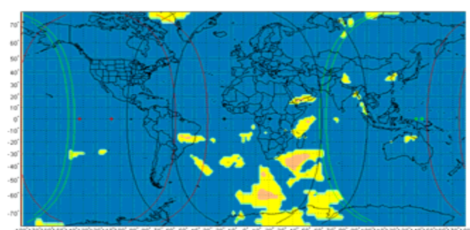
(RNP0.5)

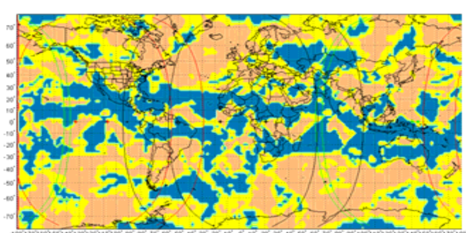




HAL = 0.3 nm

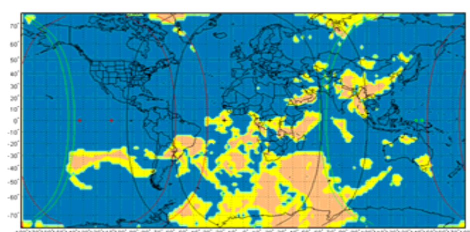
(RNP0.3)

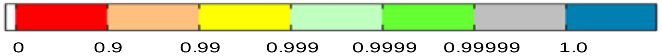




HAL = 0.15 nm

(RNP0.15)





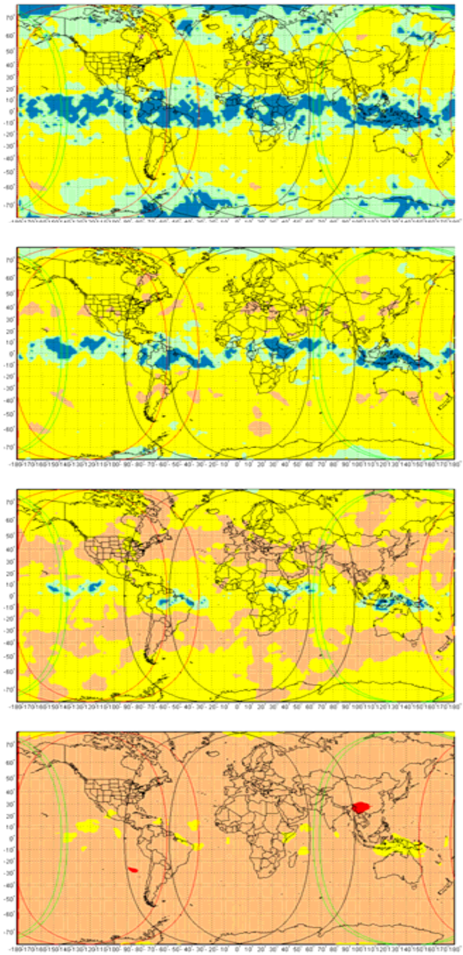
GPS and Current SBASs, 23-Satellite Degraded Constellation
(GPS URA = 4 m)

GPS/RAIM UE

<u>SA OFF</u> Design

(TSO-C196)

<u>No Baro Aiding</u>

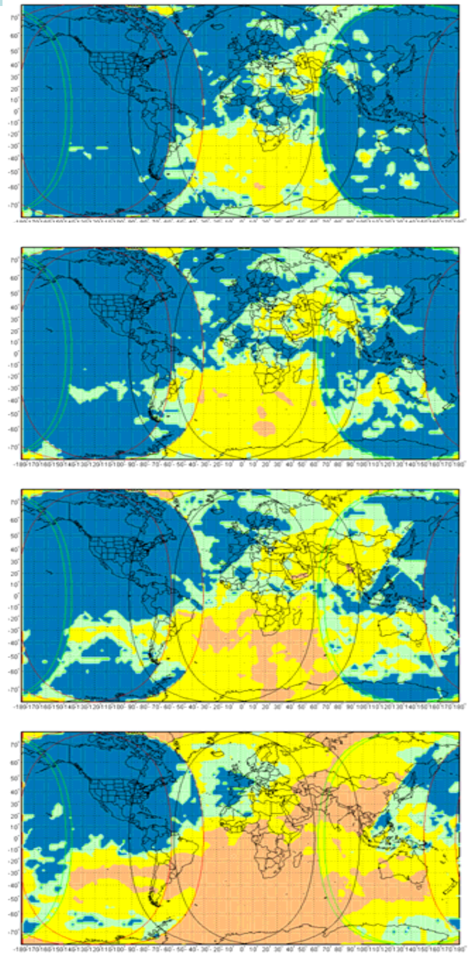


HAL = 1.0 nm
(RNP1.0)

HAL = 0.5 nm
(RNP0.5)

HAL = 0.3 nm
(RNP0.3)

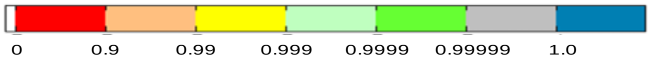
HAL = 0.15 nm
(RNP0.15)



SBAS UE

(TSO-C145/146)

<u>No Baro Aiding</u>



Conclusions for SBAS Combined Performance

- Performance obtained with SBAS UE is “always” better than obtained by GPS/RAIM performance
- SBAS user equipment maintains service when GPS service is degraded (outages) much better than GPS/RAIM user equipment
- Performance of SBAS vs. GPS improves as HALs are improved (decreased)
- SBAS service is more robust in northern hemisphere where SBAS implementations exist than in southern hemisphere

Conclusions for SBAS Combined Performance (Continued)

- Performance in Southern hemisphere reflects SBAS availability improvements when GEO ranging is enabled
  - Assumes a more precise characterization of spatial degradation is implemented (Message Type 28)
- Overall, service improves relatively little with additional satellites but degrades noticeably with satellite outages
  - Satellites in primary slots contribute much more to service than satellites in other locations
- Results confirmed improved availability for a wide range of aviation services in both hemispheres and significantly improved robustness to GPS satellite outages

Future Objectives

- Maintain civil GPS and Galileo compatibility and interoperability for end users around the world
- Raise the state-of-the-art in navigation positioning, and timing services for users worldwide
- Assess performance of GPS and Galileo open signals with advanced receiver techniques for integrity monitoring (ARAIM)
- Evaluate SBAS Performance for non-aviation users
- Improve safety-of-life services, through development of future SBAS standards for dual-frequency and multi-constellations

Thank you

Results are available as a public release:

1. *Combined Performances for SBAS Receivers Using WAAS and EGNOS*; and

2. Combined Performances for Open GPS/Galileo Receivers

Papers are available at:
http://www.unoosa.org/oosa/en/SAP/gnss/icg/providersforum.html,

http://pnt.gov/public/docs/#studies, or

http://ec.europa.eu/enterprise/policies/satnav/documents/index_en.htm

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