Navigation

SS-2004

Chapter 9 – Satellite-based navigation

9 Satellite-based navigation / Contents

9 Satellite-based navigation (1)

9.1 Introduction

- Terminology
  - Satellite-**based** navigation means navigation based on satellites, i.e. using signals transmitted by satellites
  - Modern term: GNSS = global navigation satellite system(s)

- Brief historical review
  - 1957: successful launch of **Sputnik**
  - Line-of-sight radio navigation became possible through the use of artificial satellites
  - 1960s: U.S. Navy Navigation Satellite System (NNSS), also known as **Transit**
  - “Cold-war response”: **Tsikada** (very similar to Transit)

9 Satellite-based navigation (2)

- 1980s: development of the U.S. **Global Positioning System** (GPS) with full operational capability (FOC) reached in 1995
- “Cold-war response”: **Global’naya Navigatsionnaya Sputnikovaya Sistema** (GLONASS) with FOC reached (only) in 1996

– Current developments

- Modernization of GPS
- Development of the European Galileo
- Possible further development of GLONASS

9.2 Early systems

9.2.1 Transit

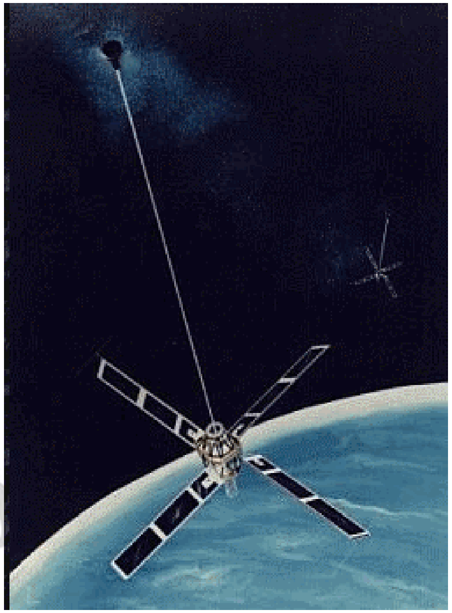
- General remarks
  - Transit was conceived in the late 1950s by Johns Hopkins Applied Physics Laboratory (APL) and deployed in the mid-1960s
  - The basic concept was triggered by U.S. studies of signals from the first Soviet **Sputnik** satellite
  - The entire Sputnik **orbit** was determined from Doppler shift data
  - **Idea**: if the satellite orbit is known, an **unknown receiver position** may be determined from the same type of Doppler measurements

9 Satellite-based navigation (4)

- Key advantage of Transit: **worldwide coverage** with periodic position updates could be obtained with just **one satellite**
- Each satellite provided **four to six position updates** per day for every user
- Additional satellites only increased the **update frequency** and improved the daily distribution of these updates
- **Six satellites** were launched until November 1961
- The objectives included providing data needed to analyze the **gravity field of the earth**
- On December 31, 1996, Transit was declared being **out of order**

9 Satellite-based navigation (5)

System architecture



- Control segment
  - Tracking stations
  - Computing center
- Space segment
  - Circular, polar orbits
  - Height: 1075 km (low-earth orbit, LEO)
  - Period: 107 minutes

Source: http://home.arcor.de/satellitenwelt/

- Signal structure
  - Two stable carrier waves at 150 MHz and 400 MHz
  - Modulation of timing marks and navigation data on the carriers
  - Observables: **Doppler shift** of the satellite signals due to the orbital motion of the satellites (high Doppler shift due to fast radial motion in low-earth orbits)

9 Satellite-based navigation (6)

– **User segment**
  - **Unlimited capacity** due to passive user receivers
  - Whenever a satellite passed above the horizon, a **single** horizontal position fix could be obtained
  - The average **time interval** between fixes varied from 35 to 100 minutes, depending on the latitude of the user and the number of operational satellites

Example of a Transit receiver
(http://home.t-online.de/home/Hbusch/satnav.htm)

9 Satellite-based navigation (7)

– **Positioning accuracy**
  - Measurements referred to **sequential positions of one satellite** as it passed above the user ➔ no simultaneous observations of several satellites were used
  - Possible motions of the user during the satellite pass had to be considered in the fix calculations, e.g. by dead reckoning (➔ **running fix**)
  - Accurate position fixes could be obtained by combining
    - the calculated **satellite positions**,
    - the **range differences** between these positions (derived from integrating the Doppler shift measurements) yielding hyperboloids of revolution,
    - and information regarding possible **motions of the receiver**

9 Satellite-based navigation (8)

- **Typical accuracies**
  - Navigation mode
    - Single-frequency receivers: ± 80 m to ±100 m
    - Dual-frequency receivers: ± 25 m
  - Surveying mode for fixed stations
    - Single point positioning: ± 5 m
    - Relative positioning: ± 0.5 m

9 Satellite-based navigation (9)

TUG

9.2.2 Tsikada

- Two parts
  - Military system
  - Civil system
- The system architecture of the civil system is very similar to Transit
  - 4 LEO satellites
  - Carrier waves at 150 MHz and 400 MHz
  - Positioning accuracy: ~ 100 m

Source: www.astronautix.com

- Further Internet sites (March 2004)
  - www.fas.org/spp/guide/russia/nav/tsikada.htm
  - www.vectorsite.net/ttgps.html ➔ Tsikada “seems to be operational”

9.3 GPS and GLONASS

Comparison of the systems (a)

Feature	**GPS**	**GLONASS**
FOC	July 17, 1995	January 18, 1996
Actual (nominal) # SV	**28** (24)	**10** (24)
# orbital planes	6	3
Orbit inclination	55°	65°
Orbit altitude	20200 km	19100 km
Revolution period	~ 12 hours	~ 11.25 hours
Ephemeris data representation	Kepler elements, extrapolation coeff.	Position, velocity, acceleration vectors

9 Satellite-based navigation (11)

Comparison of the systems (b)

Feature	GPS	GLONASS
Reference system	WGS-84	PZ-90
Signal separation	CDMA	FDMA
Almanac contents	152 bit	120 bit
Almanac trans. time	12.5 min	2.5 min
L1 frequency [MHz]	1575.42	1602.5625 – 1615.5
L2 frequency [MHz]	1227.60	1246.4375 – 1256.5

Comparison of the systems (c)

Feature	GPS	GLONASS
Type of ranging code	C/A-, P(Y)-code	S-, P-code
C/A- (S-) code freq.	1.023 MHz	0.511 MHz
P-code frequency	10.23 MHz	5.11 MHz
Availability	Non selective (since May 2000)	Non selective
Time synchronization	GPS time, UTC (USNO)	GLONASS time, UTC (SU)
Ground track repeat period	1 siderial day	8 siderial days

Combining GPS and GLONASS

- **Engineering principle**:
  "adding correctly weighted observables
  always decreases the variance of a measurement"

Example: Ashtech GG24

- **Benefits**
  - Accuracy: only minor improvements
  - Availability: depends on type of system integration (raw measurements vs. solved positions)
  - Reliability: increase due to independence of systems
  - Integrity: increase of receiver-autonomous integrity monitoring (RAIM) capability

9 Satellite-based navigation (14)

- **RAIM** …
  - may prevent an unhealthy satellite from degrading typical GPS-only performance by **detecting and removing erroneous signals**
  - **benefits tremendously** from an increased number of satellites, since it uses redundant measurements in its computations

– **Difficulties**

- Different reference frames
- Different time systems
- Different signal structures

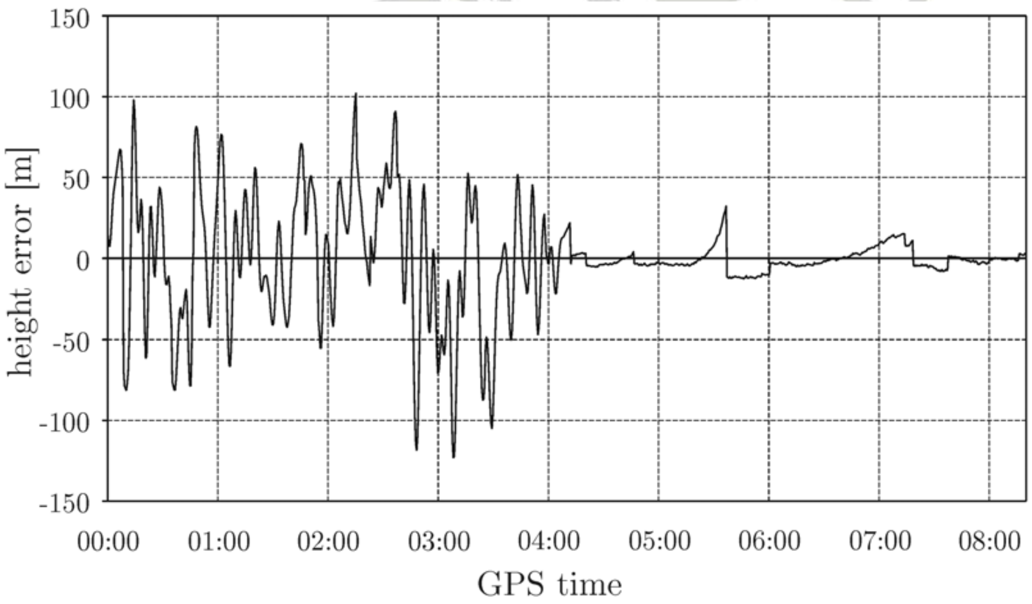
– Future: Integrated **GPS/Galileo** receivers

Chapter 10 – Augmentation systems

10 Satellite-based navigation / Contents

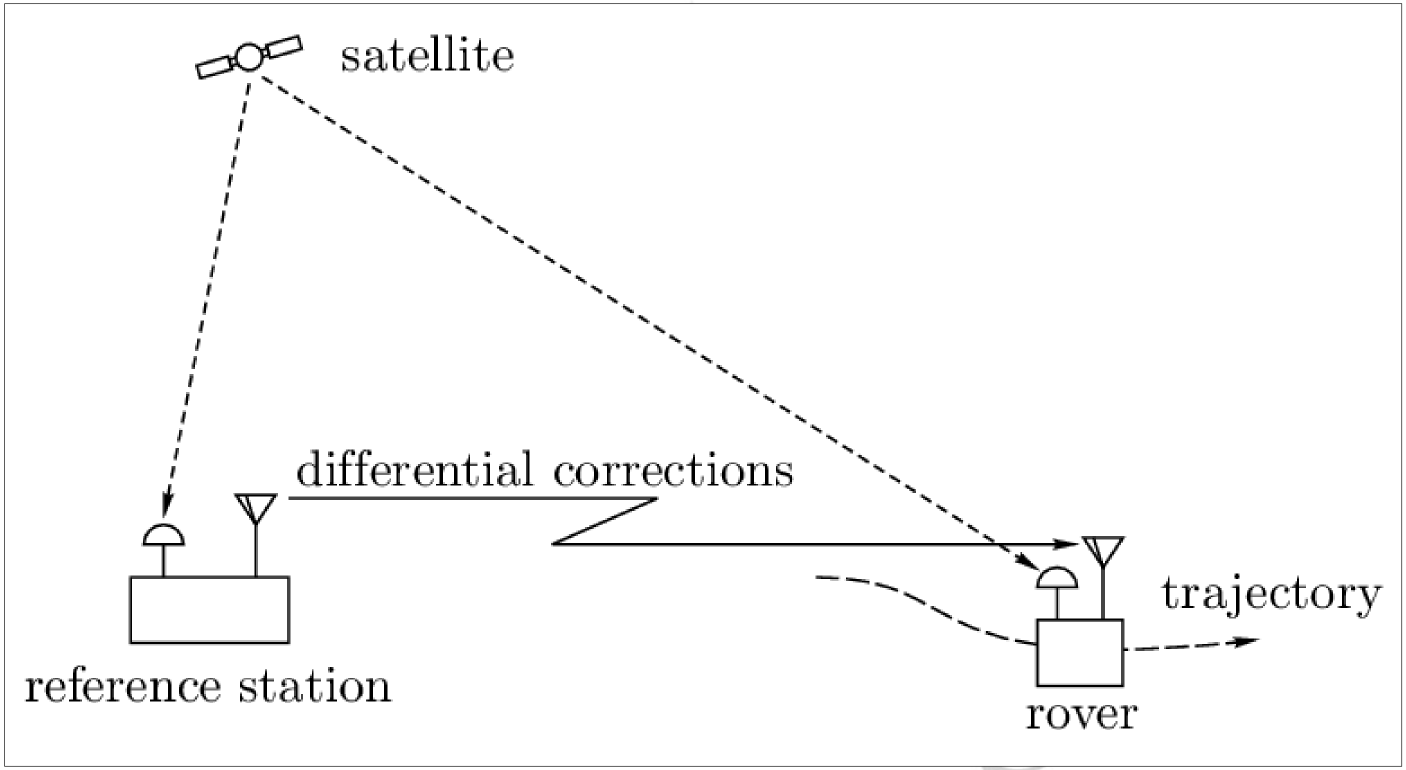
10.1 Introduction

- End of SA ➔ reconsideration of many differential GPS (DGPS) services
- Future: GNSS augmentation systems
  - DGNSS
  - Integrity monitoring



10.2 Differential GPS

10.2.1 Principle



- Mathematical derivation ➔ see labs

10.2.2 Systems and concepts

- Terminology
  - **Conventional DGPS** uses raw or smoothed code PRs
  - **Precise DGPS** uses phase PRs
  - **Real-Time-Kinematics** (RTK) is relative kinematic positioning

	Conventional DGPS		Precise DGPS
Observables	raw code pseudoranges	smoothed code pseudoranges	phase pseudoranges
Range of application	some 1000 km	some 100 km	some 10 km
Positioning accuracy	< 10 m	< 1 m	< 0.1 m
Main drawback	limited accuracy	limited range	ambiguity resolution, range

10 Augmentation systems (4)

- Single versus multiple reference station concept
  - **Single reference station concept**
    - Very simple… **BUT**

      positional accuracy decreases with increasing distance from the base station

10 Augmentation systems (5)

– **Multiple reference station concept**

- **Advantages**
  - (Almost) no accuracy decrease with increasing station separation (➔ limited spatial decorrelation)
  - Extended coverage
  - Increased reliability and integrity

- **Disadvantages**
  - Increased costs for network installation and maintenance
  - More complex hardware and software
  - Additional latency introduced by intra-network communication

10 Augmentation systems (6)

10.2.3 Multiple reference station concept

- Approaches
  - Currently two main approaches are in use
    - Measurement-domain approach (➔ scalar correction data)
    - State-space approach (➔ vector of correction data)

Scalar algorithms	Vector algorithm
Extended DGPS	Wide Area DGPS (WADGPS)
Local Area DGPS (LADGPS)	Worldwide DGPS (WWDGPS)

10 Augmentation systems (7)

- **Wide Area DGPS (WADGPS)**
  - **Network of monitor stations** tracks all satellites in view using dual-frequency receivers to derive position-dependent vectors of corrections
    - **Ionospheric corrections** ➔ modeling the TEC using the dual-frequency data (e.g. via the Klobuchar model)
    - **Orbital corrections and clock biases** ➔ network solution of ionosphere-corrected pseudoranges

10.2.4 Data transfer

- **Radio links**
  - General remarks
    - Data transfer in real-time is based on **telemetric links** (controlled radio links)
    - Telemetric links require **compatible hardware** at the reference station and at the rover receivers
  - Link characteristics
    - **Types** … ground-based vs. space-based
    - **Parameters** … frequency, power, data rate
    - **Formats** … proprietary vs. receiver-independent

10 Augmentation systems (9)

– **Ground-based** data transmission

System	Frequency	Data rate [bps]	Range [km]
Eurofix	LF	30	1.500
Radio beacons	MF	100	300
Radio data system	VHF	1.000	100
GSM	UHF	9.600	30
GPRS	UHF	44.000	30
UMTS	UHF	2.000.000	10

(Indicative/theoretical values)

– **Space-based** data transmission
➔ typically via geostationary satellites

10 Augmentation systems (10)

- **Data formats**
  - Some manufacturers of DGPS receivers use proprietary formats to compress the data to transmit more data per time unit
  - For non-autonomous operation, **receiver-independent** formats must be used to transmit correction data
  - **RTCM format**
    - Internationally accepted standard format for the transmission of correction data was proposed by Special Committee 104 of the U.S. **Radio Technical Commission for Maritime Services**

10 Augmentation systems (11)

– **Several versions of the RTCM format exist**

- **Version 2.0**

  ... contains range and range-rate corrections for (C/A- and P-) code pseudoranges

- **Version 2.1**

  ... contains additionally phase pseudorange corrections and raw observables

- **Version 2.2**

  ... provides version 2.1 data also for GLONASS satellites

- **Version 2.3**

  ... considers recent developments (end of SA)

10 Augmentation systems (12)

– **64 message types are available** (not all yet defined)

- Format of messages is (almost) identical to the GPS navigation message (i.e., sequence of 30-bit words)
- Each message starts with a two- (or three-) word header which contains
  – fixed preamble
  – message type identifier
  – time tag (Z-count)
  – sequence number
  – message length

- Data amount required for code pseudorange corrections
  – 6 satellites ... ~ 480 bits

10 Augmentation systems (13)

10.3 DGPS services

- **General remarks**
  - **Sources of differential correction data**
    - Autonomous operation ... mainly for *precise* DGPS
    - Provided services ... mainly for *conventional* DGPS
  - **Features**
    - Continuously operating (stationary) reference stations (CORS)
    - Operating on global, continental, or regional scale
    - Characterized in terms of accuracy, availability, coverage, costs

10 Augmentation systems (14)

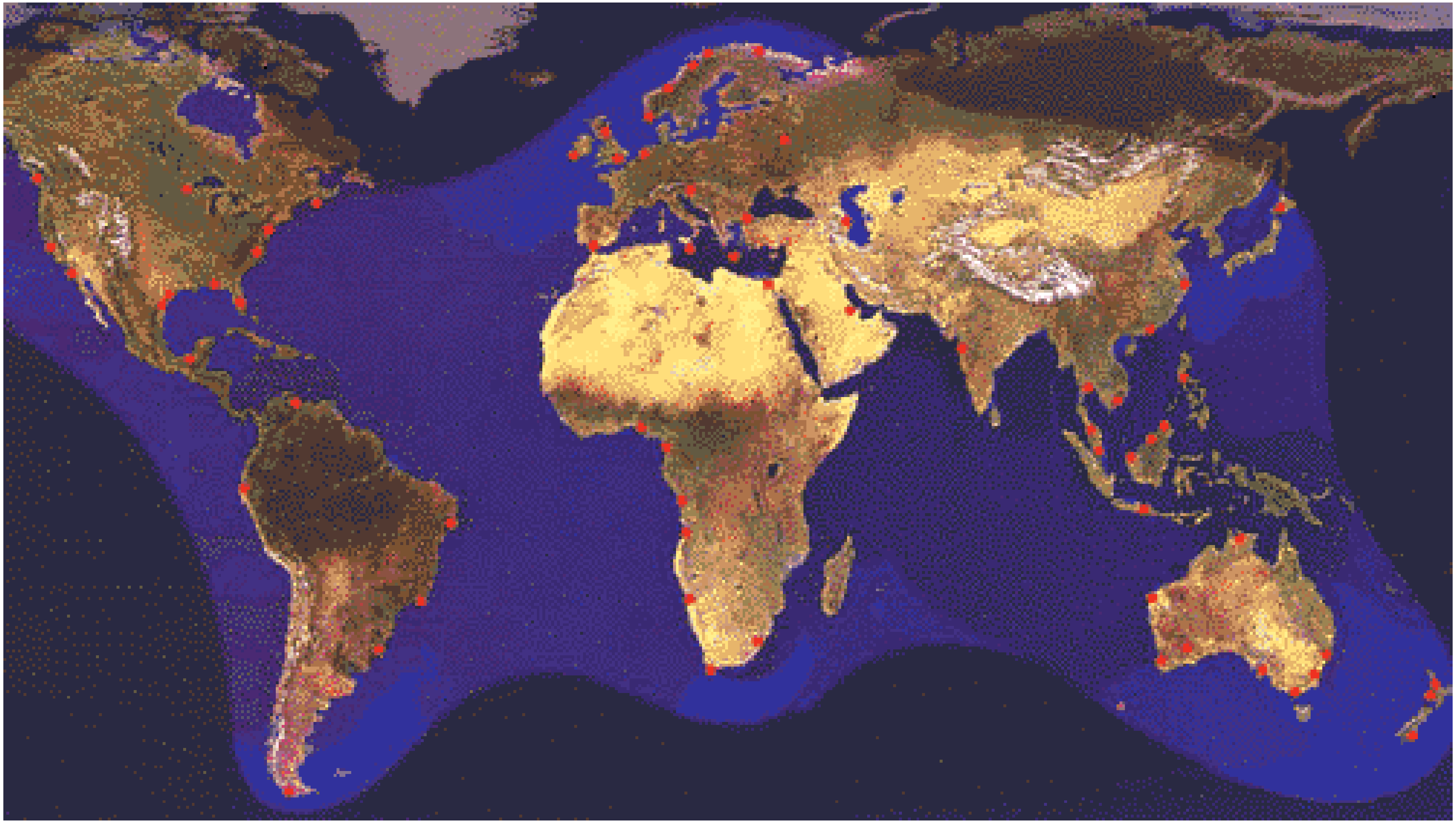
10.3.1 Examples

– **Europe**

- **Omnistar**
  - (Almost) global WADGPS service operated by Fugro providing code range corrections
  - European reference network consists of 16 reference stations
  - The (scalar) corrections in RTCM 2.0 format are transmitted to the rovers via communication satellites
  - Small and lightweight Omnistar receivers interface directly to the DGPS capable receivers
  - The service is not free of charge

10 Augmentation systems (15)

Omnistar reference stations and coverage area



10 Augmentation systems (16)

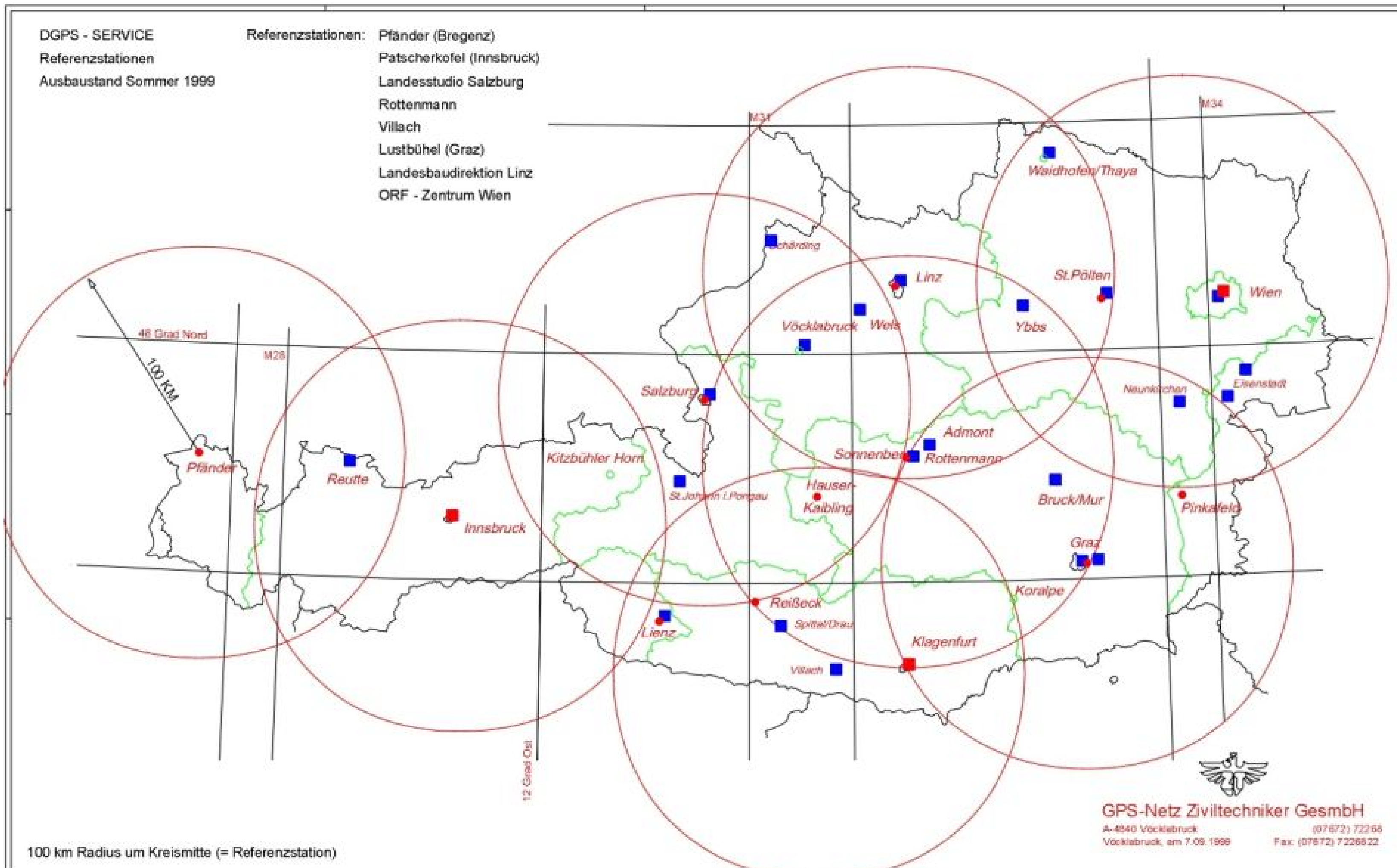
- **Austria**
  - Currently, no nationwide Austrian service is available
  - Former **Mercator** service
    - **Partners**
      - Federal Office of Metrology and Surveying (**BEV**)
      - Austrian Broadcasting Corporation (**ORF**)
      - Institute for Space Research of the Austrian Academy of Sciences (**ÖAW**)
      - Austrian surveying and consulting group (**GPS Netz**)
    - **Service provided RTMC-2.2 data**
      - Code range corrections for (almost) 100% of Austria
      - Phase range corrections for about 40% of Austria

10 Augmentation systems (17)

- Tracking network consisted of **15 reference stations** and was based on the **Austrian GPS Reference Network** (AREF) which is a realization of ITRF
- Correction data were transmitted by the ORF via **Ö1** using more than 300 stations (**transmitters**, **repeaters**)
- Modulation was performed by the UHF subcarrier technique DARC/Swift (System for Wireless Infotainment Forwarding and Teledistribution)

10 Augmentation systems (18)

Mercator DGPS reference stations



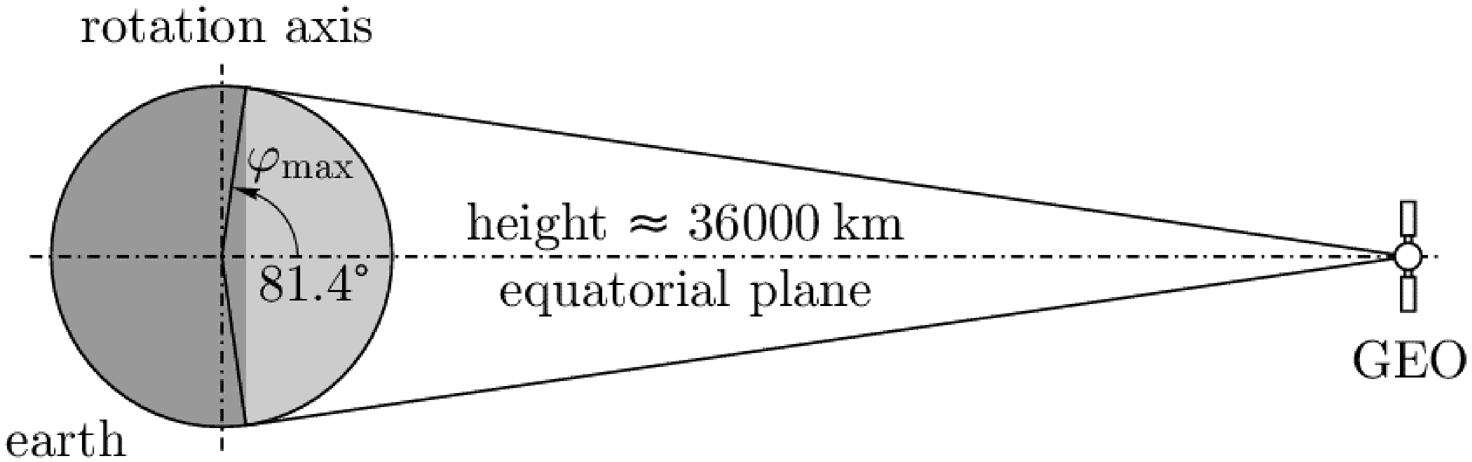
10 Augmentation systems (19)

10.3.2 Services under development

- **Satellite-Based Augmentation Systems (SBAS)**
  - Services
    - USA ... Wide Area Augmentation System (**WAAS**)
    - Japan ... MT-Sat Augmentation System (**MSAS**)
    - European Geostationary Navigation Overlay Service (**EGNOS**)
  - Components
    - WADGNSS
    - GNSS Integrity Channel (GIC)
    - GEO Ranging (GEO-R)

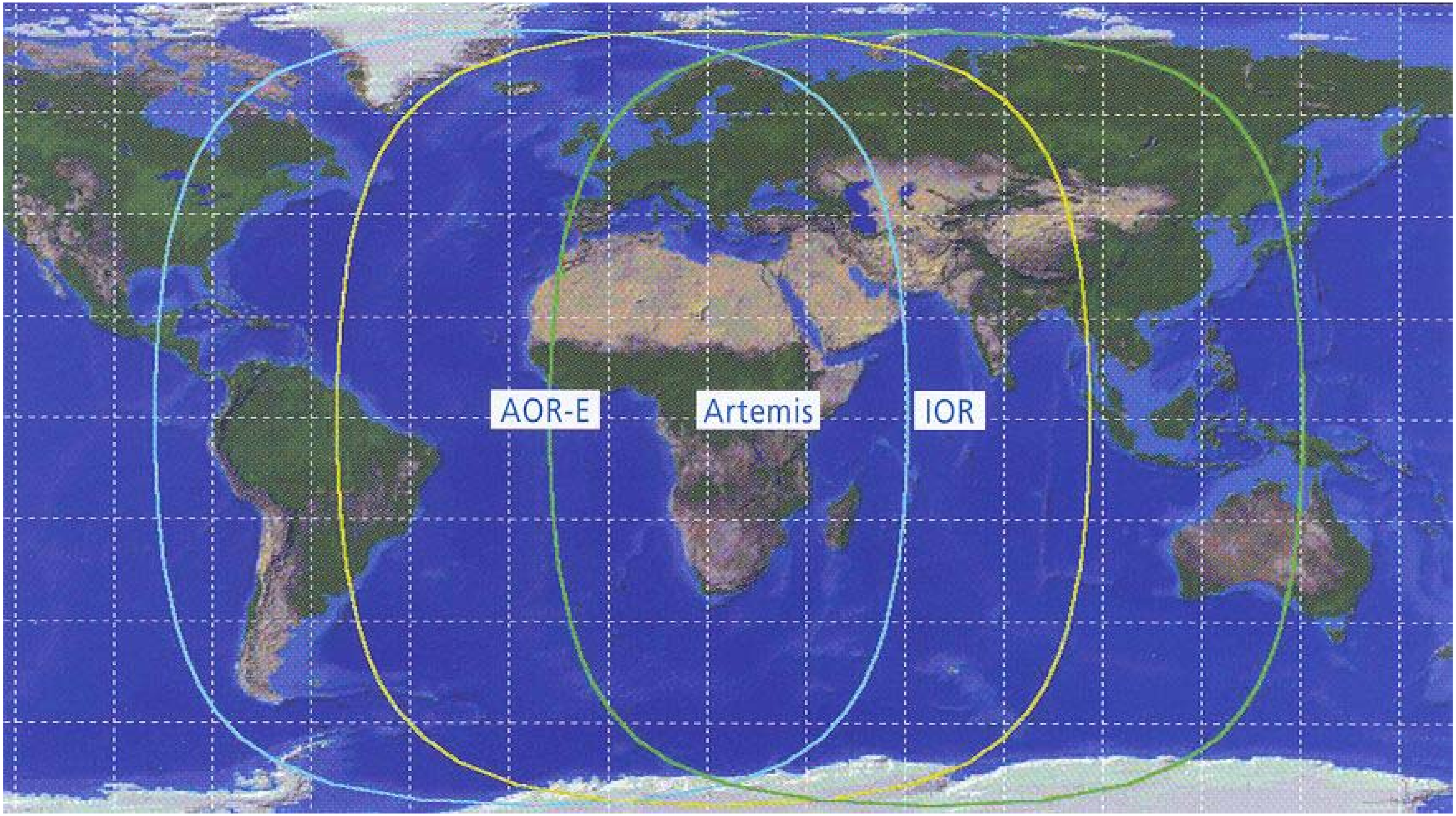
10 Augmentation systems (20)

Visibility of a GEO from the earth



10 Augmentation systems (21)

EGNOS space segment coverage area

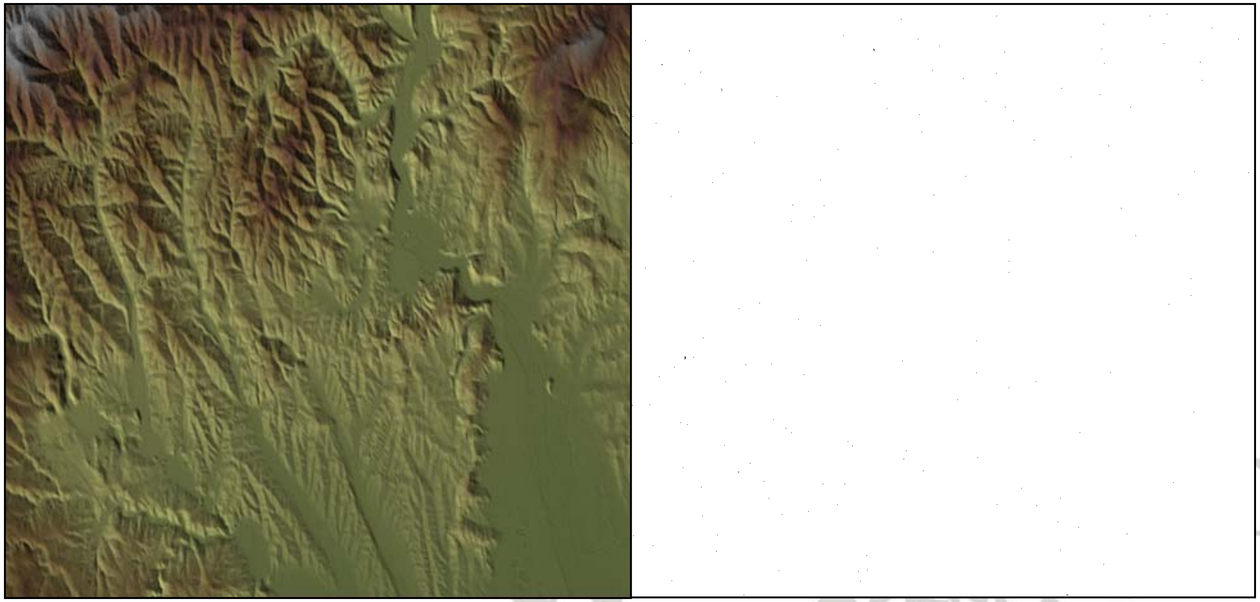


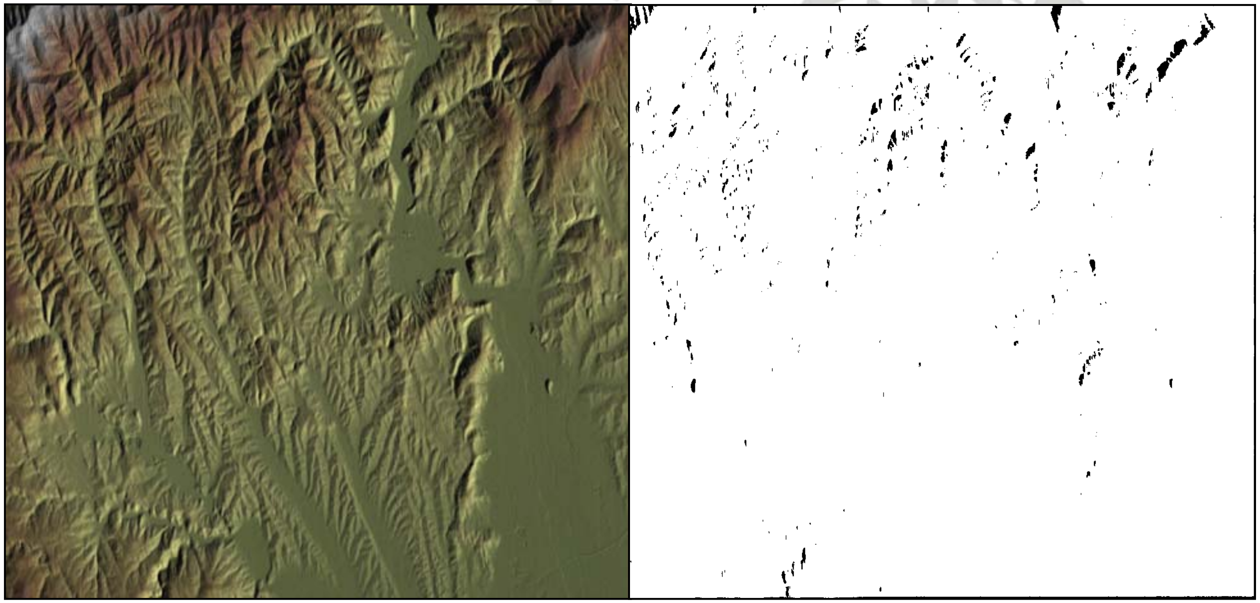
10 Augmentation systems (22)

- EGNOS simulations for Austria
  - Direction vectors to the GEO satellites

Satellite	Graz		Innsbruck	
	Azimuth	Elevation	Azimuth	Elevation
AOR-E	219°	28°	215°	30°
IOR	122°	18°	118°	15°

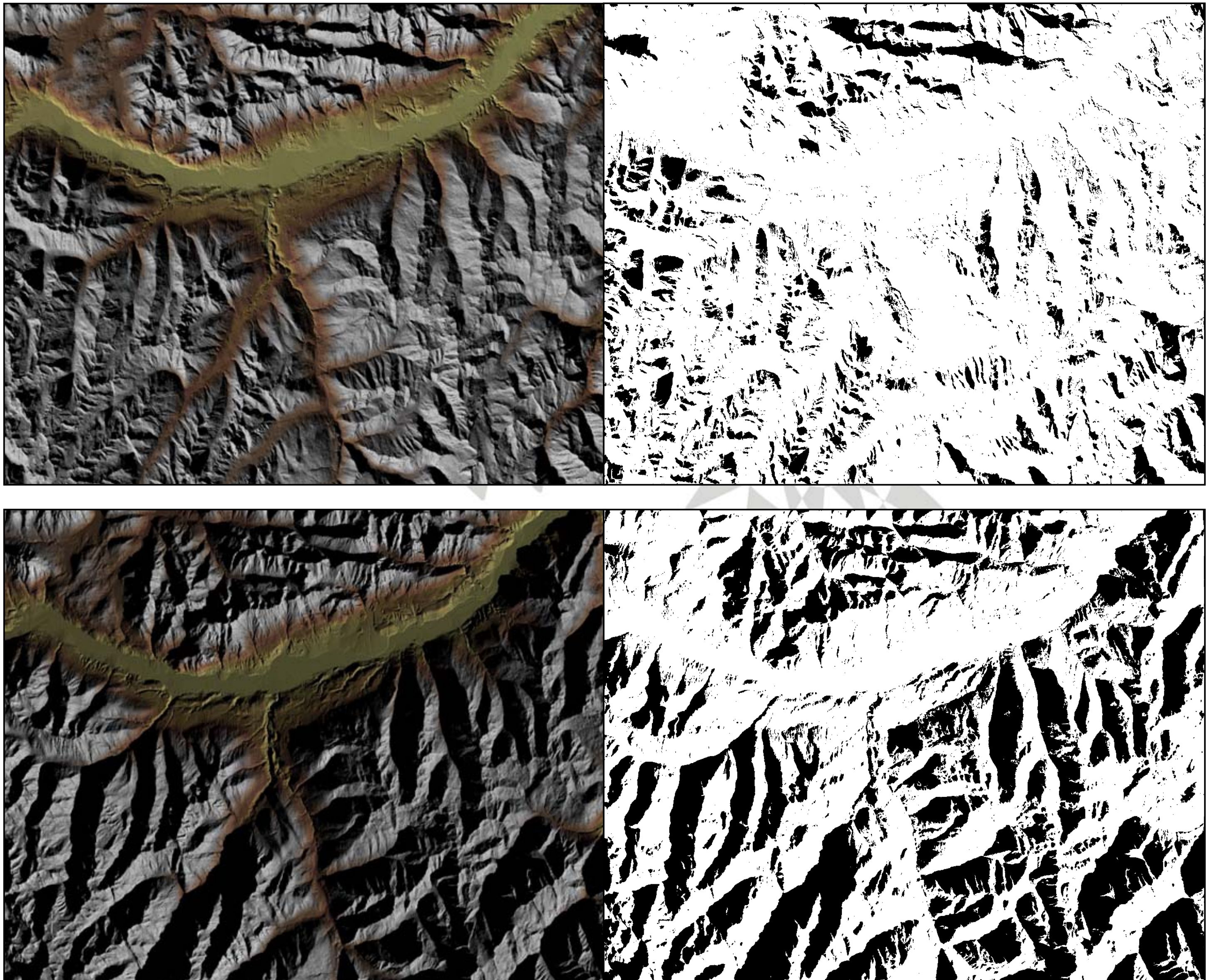
10 Augmentation systems (23)





- GEO visibility at Graz
  - AOR-E: 99,9%
  - IOR: 98.6%

10 Augmentation systems (24)



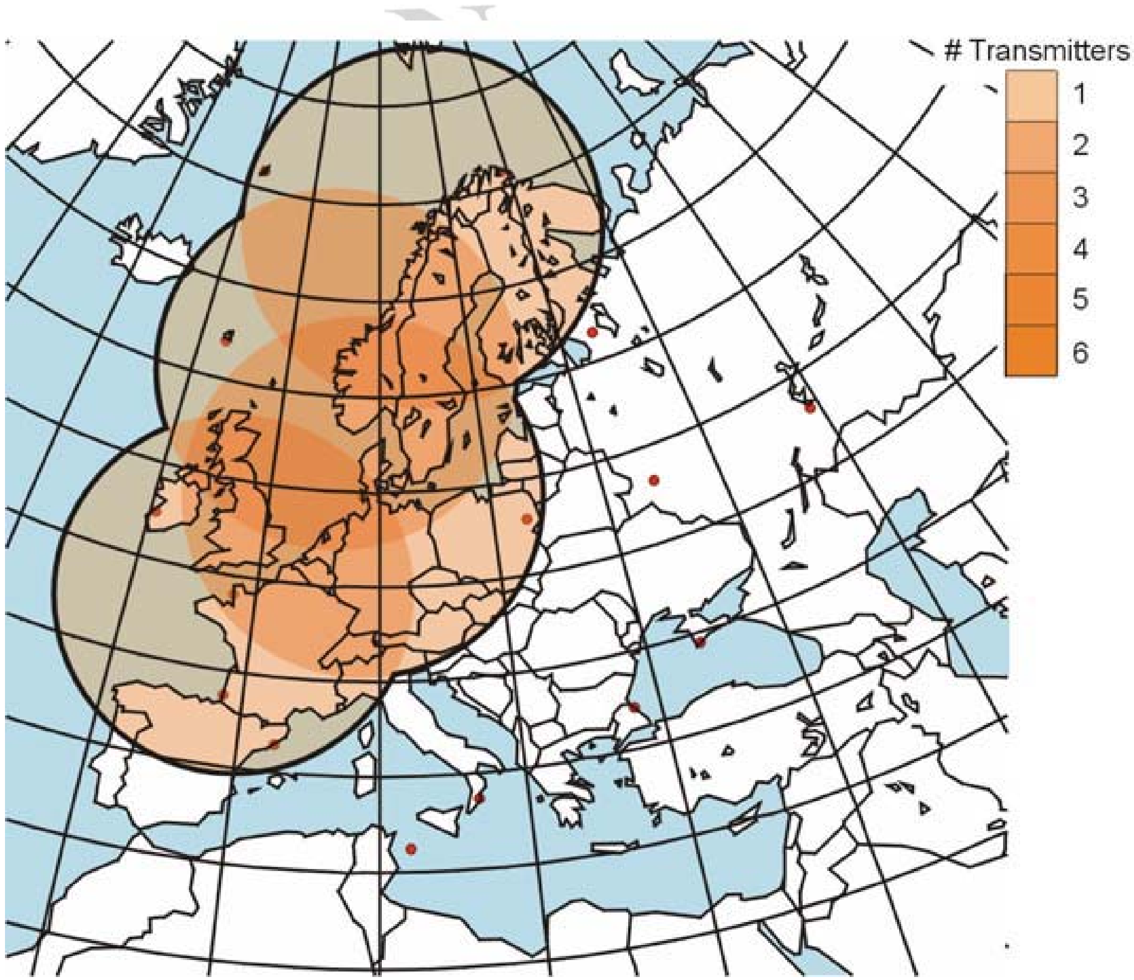
- GEO visibility at Innsbruck
  - AOR-E: 85.9%
  - IOR: 61.4%

10 Augmentation systems (25)

- **Eurofix**
  - **Principle**
    - Based on the terrestrial infrastructure of Loran-C
    - Modulation scheme developed by Delft University of Technology
  - **Features**
    - Low data rate
    - High transmission power
    - Good penetration into urban areas
  - **Accuracy**
    - ~ 3 m ... single reference station
    - ~ 1 m ... multiple reference stations

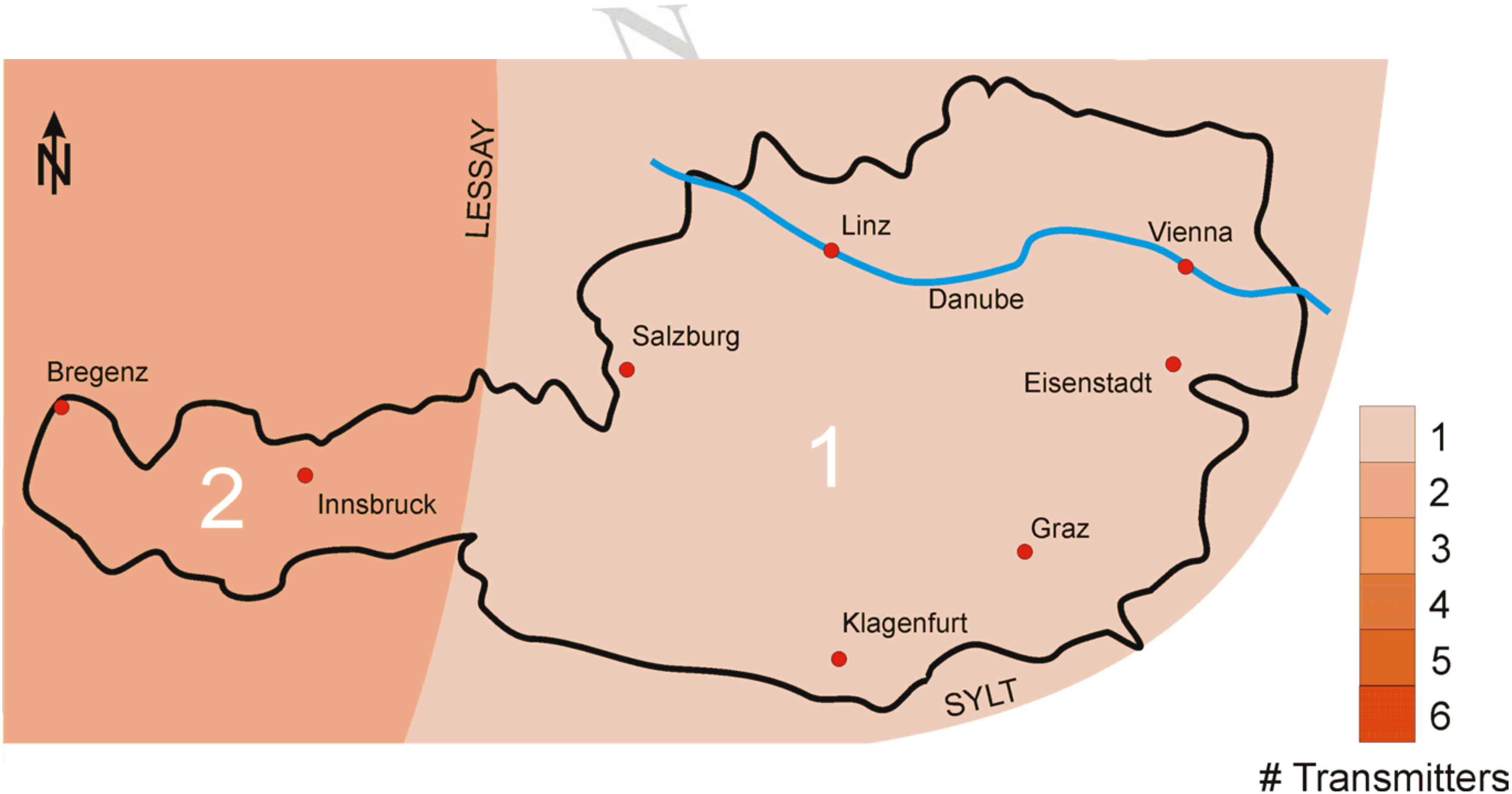
10 Augmentation systems (26)

Current status: Eurofix feasibility phase



10 Augmentation systems (27)

Current coverage in Austria



10.4 Future of DGPS

- **Expectations**
  - Conventional differential services will be replaced by **superior augmentation services** that also provide integrity information
  - High-accuracy services might be phased out when real-time centimeter accuracy will become available (e.g., via multi-carrier ambiguity resolution)

- **Reasons**
  - Switch-off of SA
  - Modernization of GPS (more civil signals)
  - Introduction of Galileo

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