Precise GNSS positioning
Threats and opportunities

Kees de Jong

Department of Mathematical Geodesy and Positioning
Delft University of Technology
The Netherlands

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Contents

Modernized GPS and Galileo

GNSS vulnerabilities

Integrated GPS/Galileo ambiguity resolution

Major error sources

Trends in RTK positioning

GPS modernization

No Selective Availability (SA)

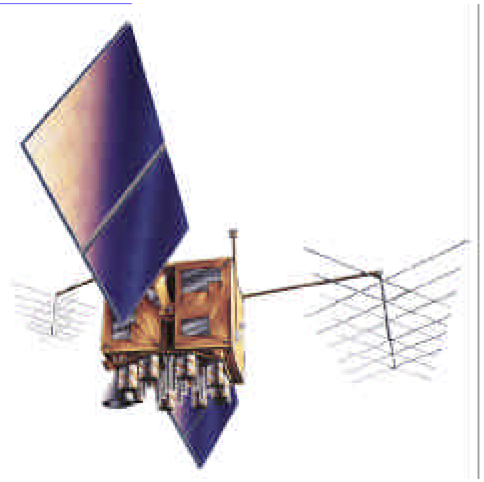
Second civil signal on L2

Third civil signal on new L5 frequency (1176.45 MHz)

Switched off on 2 May 2000

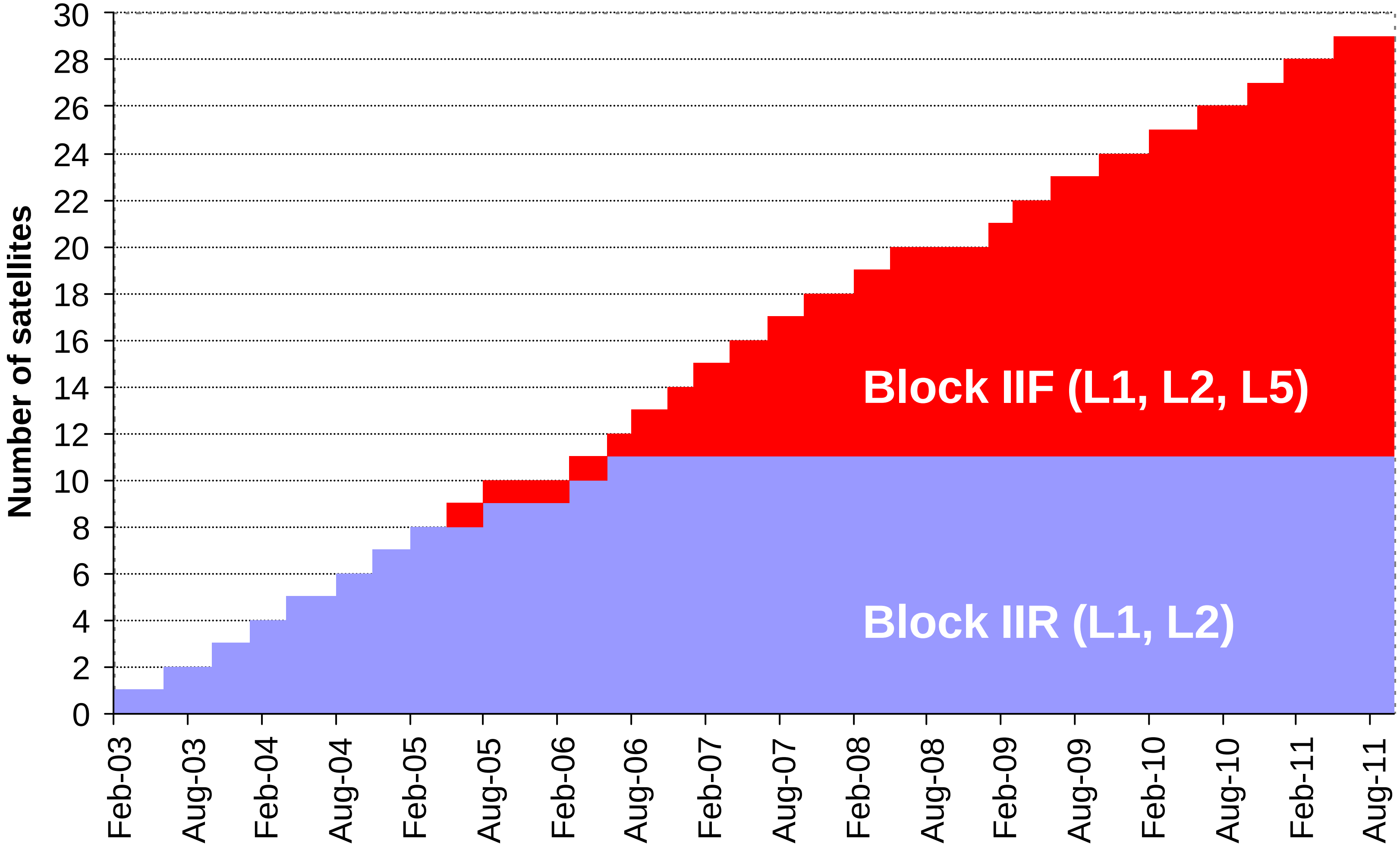
Availability of new GPS signals

Block IIR
New civil signal on L2
Stronger signals on L1 and L2
First launch in 2003



Block IIF
L5 frequency (1176.45 MHz)
New civil signals on L2 en L5
Stronger signals on L1, L2 and L5
First launch 2005

Availability of new GPS signals



Galileo orbits and frequency bands

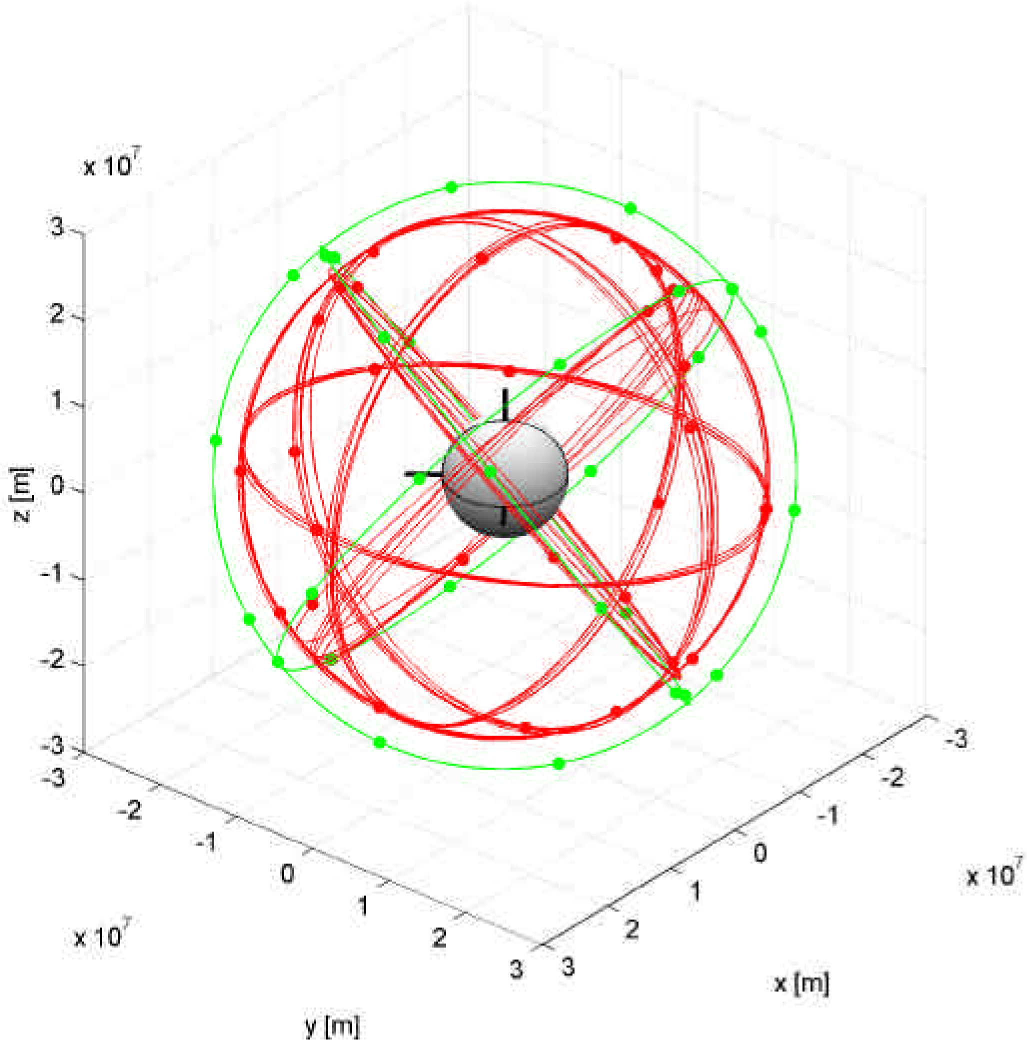
Orbits	
Orbital planes	3
Satellites/plane	10
Semi-major axis	29900 km
Inclination	56°

Frequency bands	
E1	1587-1591 MHz
E2	1559-1563 MHz
E4	1254-1258 MHz
E5	1164-1214 MHz
E6	1260-1300 MHz

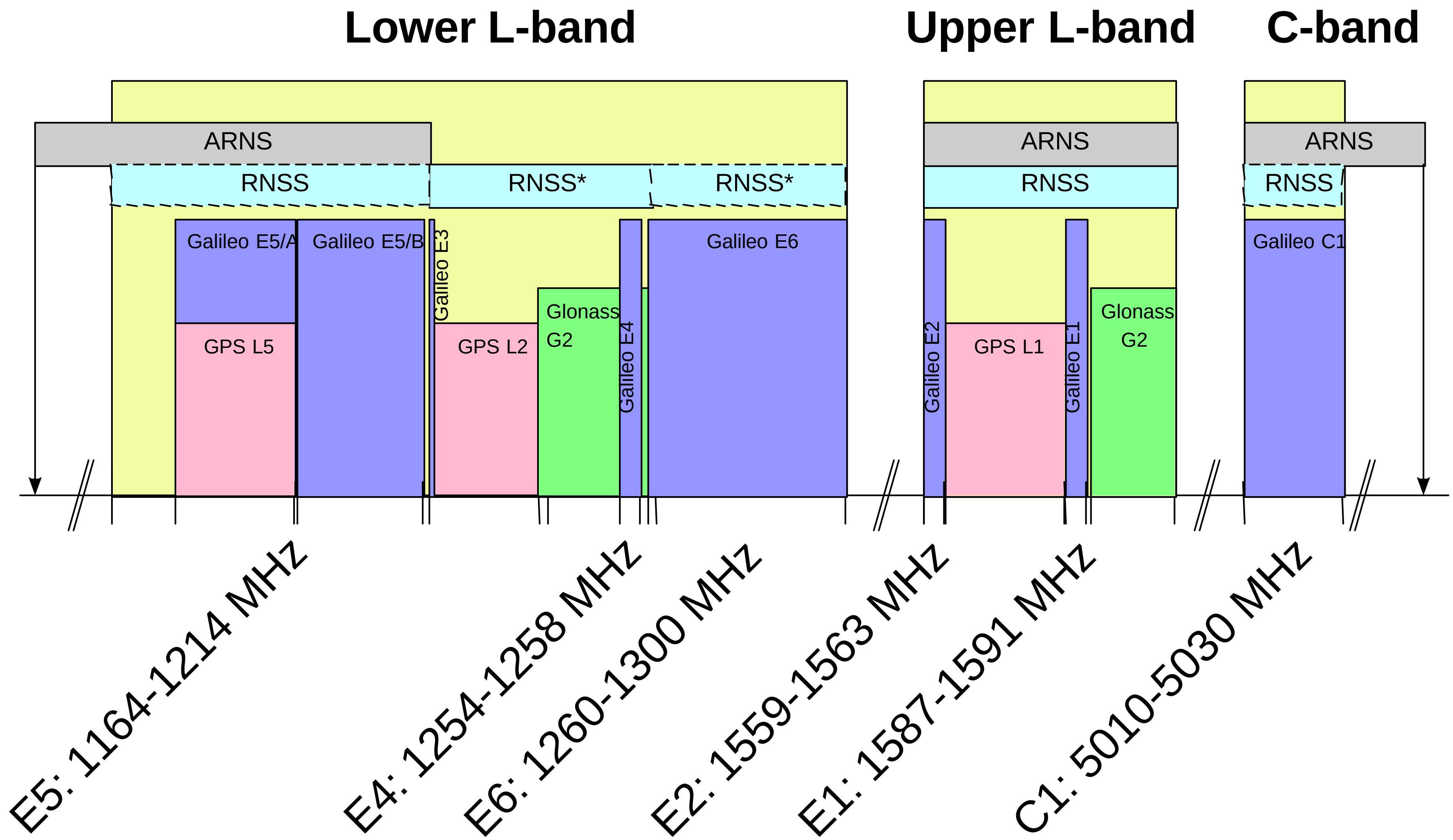
Satellite constellation

GPS

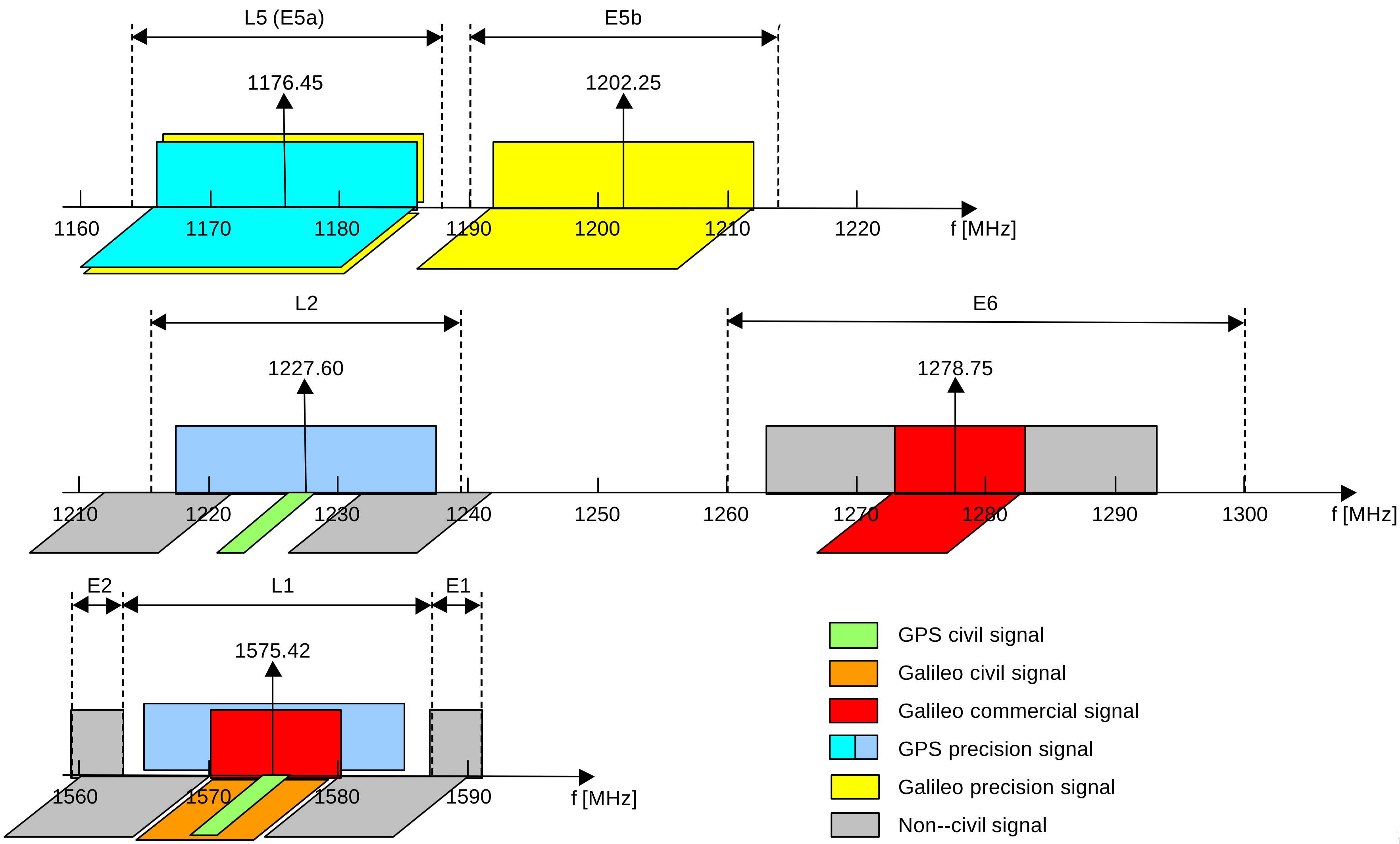
Galileo



GNSS frequency allocation



GPS and Galileo signals



Galileo schedule

Official go-ahead on 26 March 2002

First experimental satellite in 2004
(Galileo System Test Bed)

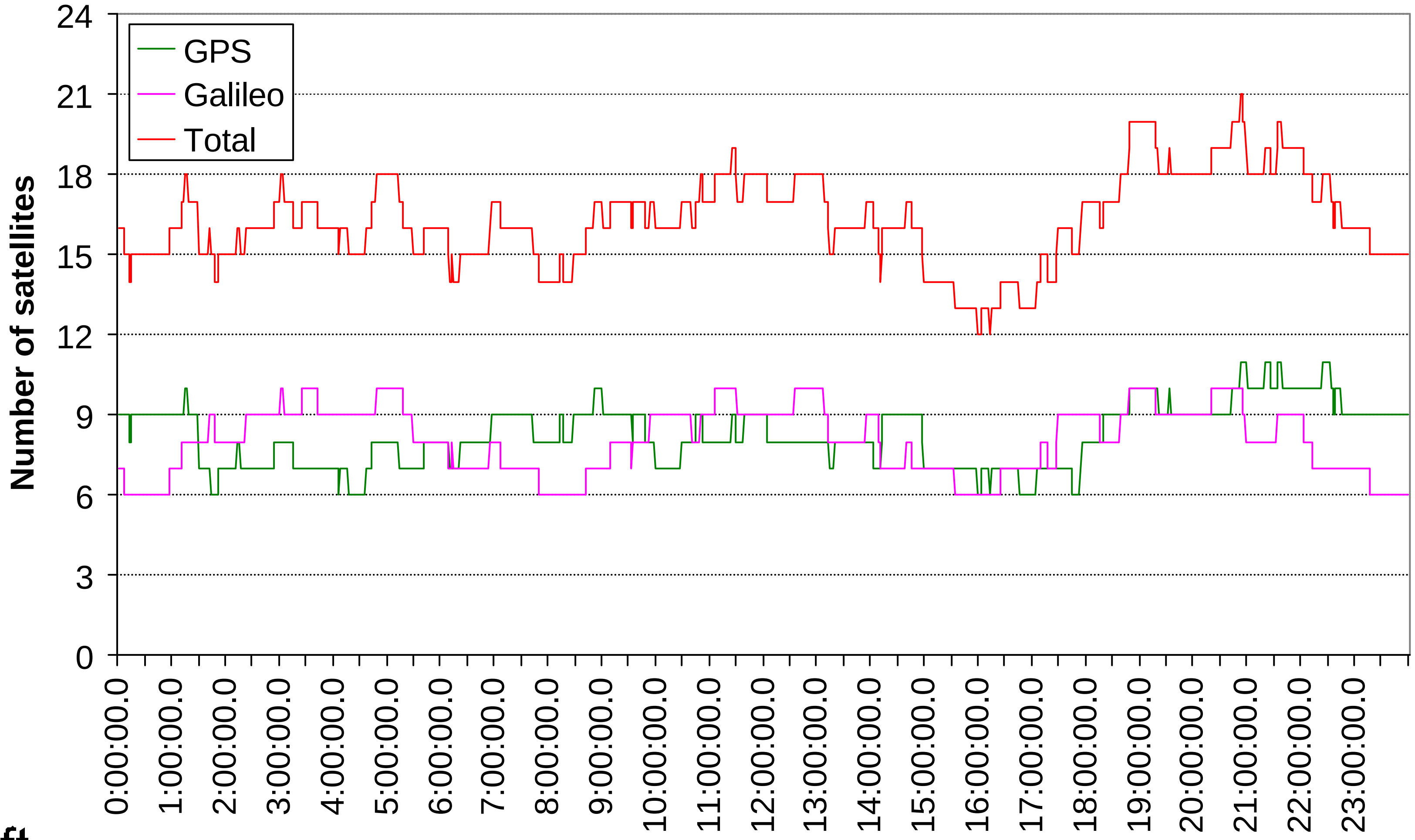
First four operational satellites in 2005-2006

Full operational constellation in 2008

See also http://www.europa.eu.int/comm/energy_transport/en/gal_en.html

Visible satellites

Location: Presidente Prudente   Date: 11 July 2002   Minimum elevation: 10°



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GPS system vulnerabilities

See Volpe vulnerability report (august 2001)
http://www.navcen.uscg.gov

Unintentional interference
Radio-frequency interference (RFI)
GPS testing
Ionosphere (solar maximum)
Spectrum congestion

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GPS system vulnerabilities

Intentional interference
Jamming: denial of use of GPS
Spoofing: broadcast wrong GPS-like signals
Meaconing: rebroadcast GPS signals
System damage: satellites or ground control segment

Human factors
Errors, over-reliance, lack of knowledge/training

Jamming

Characteristics
Simple, 1 watt: 10/85 km (loss/no acquisition) GPS-like, 1 watt: 1000 km (no acquisition)

Jammers

Russian, 4 Watt, L1 and L2, GPS and GLONASS, US$ 4,000

USA, 1 Watt

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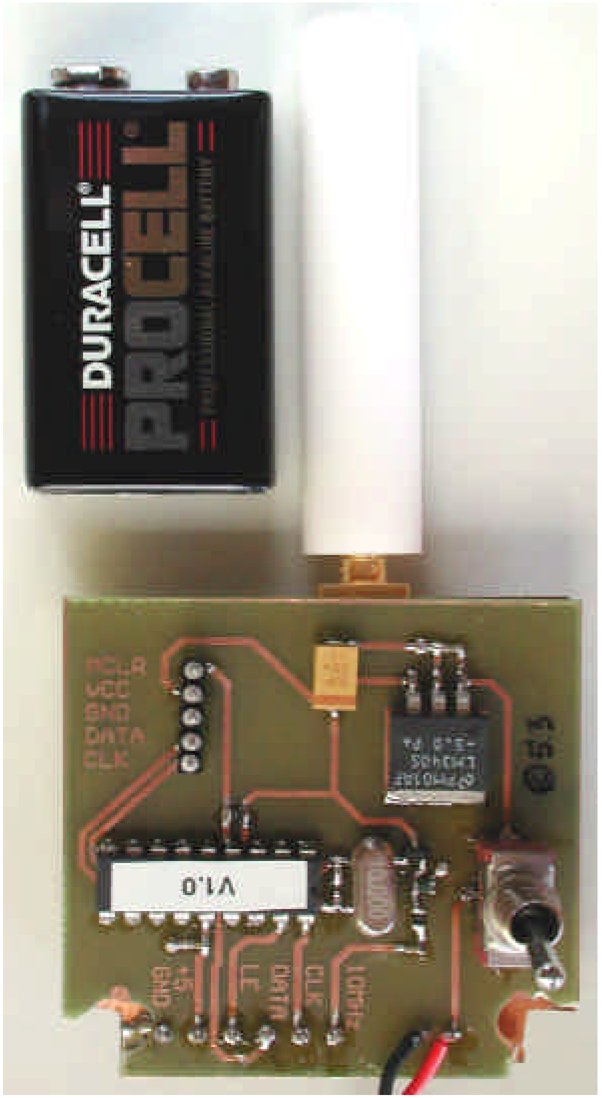
Miniature L1 jammer

TNO-FEL prototype jammer
1 mW output
Range > 125 m
Power consumption 9 V, 30 mA
Size of one cubic inch feasible



TNO-FEL: Physics research lab of the Netherlands organization for applied research

Sources of interference

Technical enthusiasts

- Students or people that cannot withstand the challenge

Criminals

- Car or cargo theft, free access to toll-roads

Terrorists

- Block airports, rescue and police

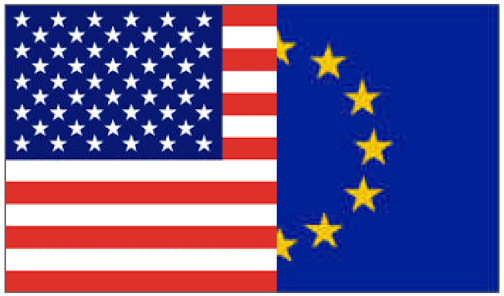
Military

- Jam potential enemy to deny use of GPS, Galileo and Glonass signals

Precise GNSS positioning

Carrier ambiguity resolution is the key to precise positioning with a Global Navigation Satellite System (GNSS) such as

I n t e g r a t e d



GPS/Galileo

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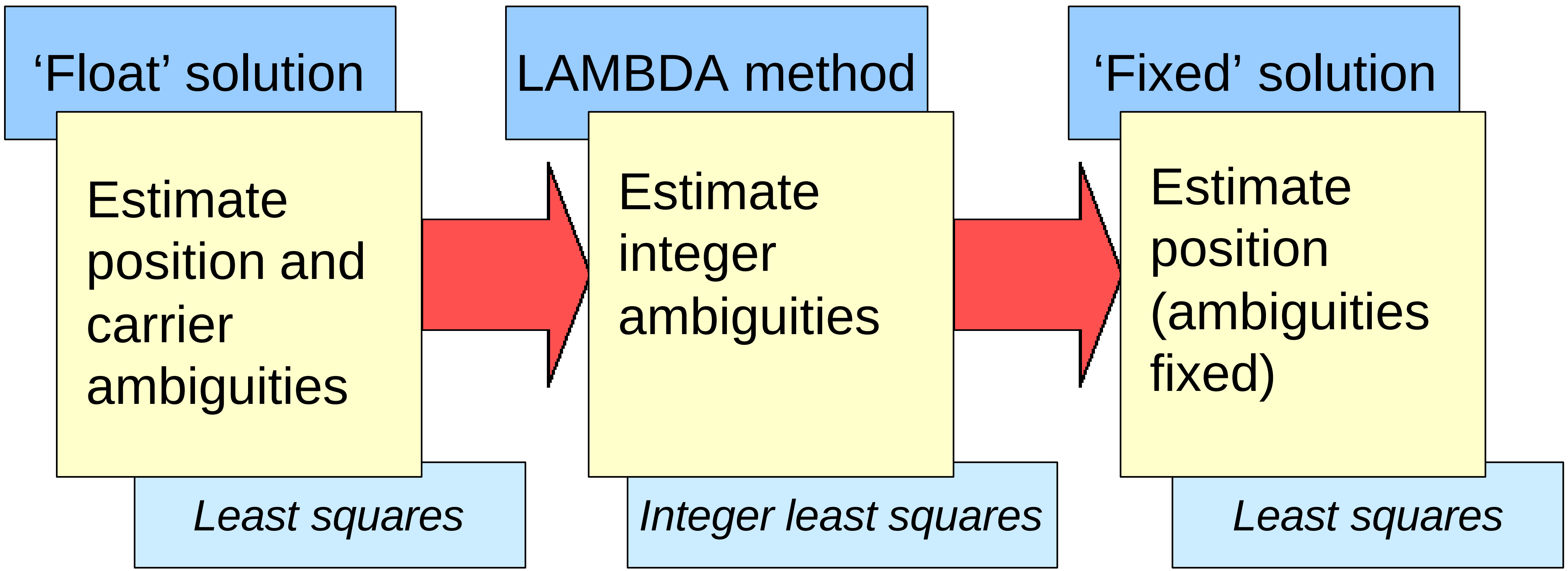
GNSS processing steps



Success-rate

Probability (number in interval [0-100%]) of fixing the carrier ambiguities to their correct integer values

Requires satellite almanac and approximate user position, but no actual data

Ionosphere models

Ionosphere float (long baseline)

New ionosphere parameter for each satellite at each observation epoch (equivalent to eliminating ionosphere)

Ionosphere weighted (medium baseline)

New ionosphere parameter for each satellite at each observation epoch constrained by *a priori* standard deviation

Ionosphere fixed (short baseline)

Ionosphere assumed absent

Design parameters - frequencies

GPS	
L1	1575.420 MHz
L2	1227.600 MHz
L5	1176.450 MHz

Galileo	
E2-L1-E1	1575.420 MHz
E5b	1202.025 MHz
E6	1278.750 MHz

Design parameters

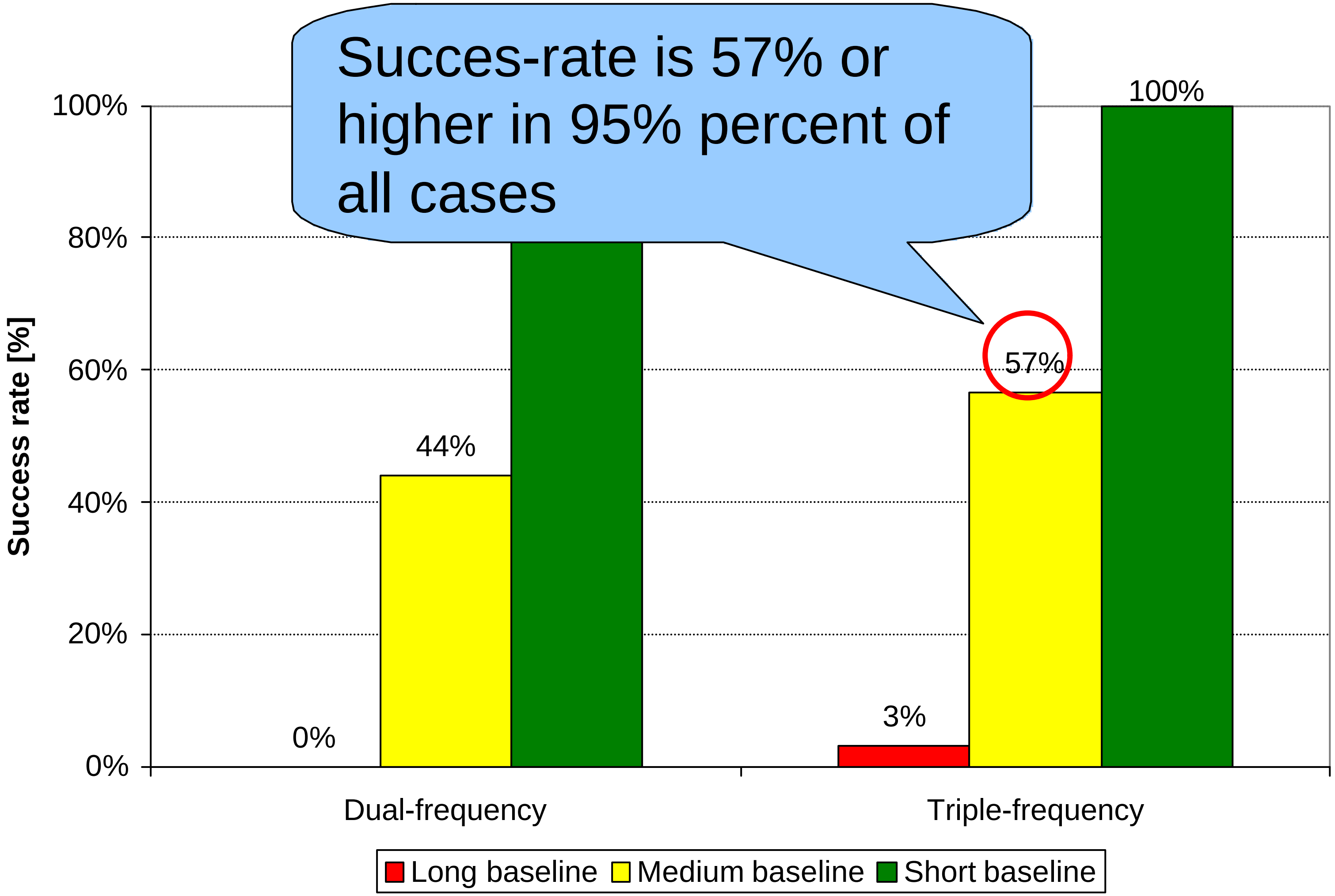
Computation of instantaneous success-rates
(single-epoch ambiguity resolution)

Location:	Presidente Prudente (22° S, 51° W)
Date:	11 July 2002
Minimum elevation:	10°
Standard deviation carrier:	0.003 m
Ionosphere weight:	0.05 m (medium baseline only)

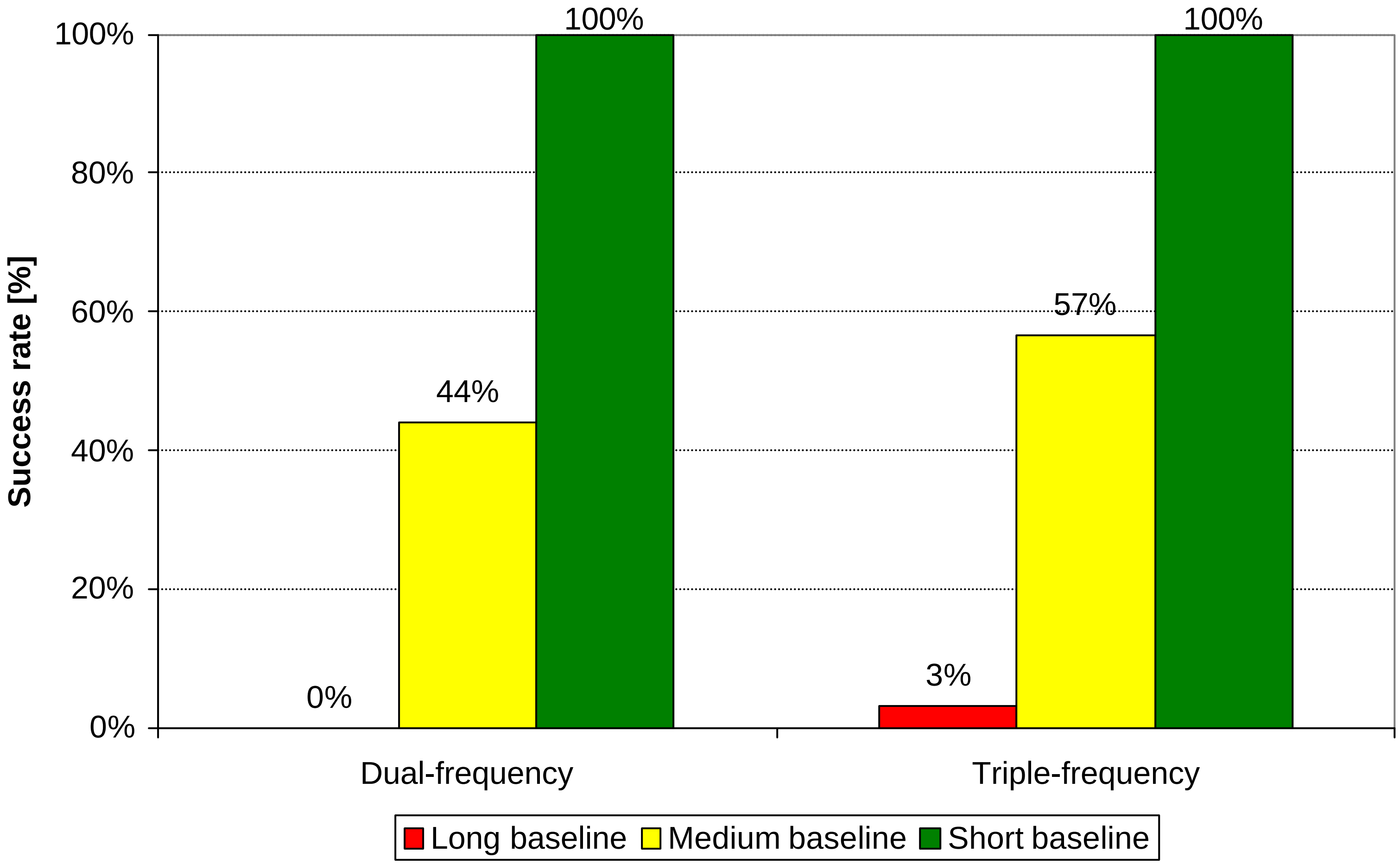
Design parameters - code observations

Standard deviation code			
L1	0.30	E2-L1-E1	0.15
L2	0.30	E5b	0.10
L5	0.10	E6	0.10

Interpretation of results

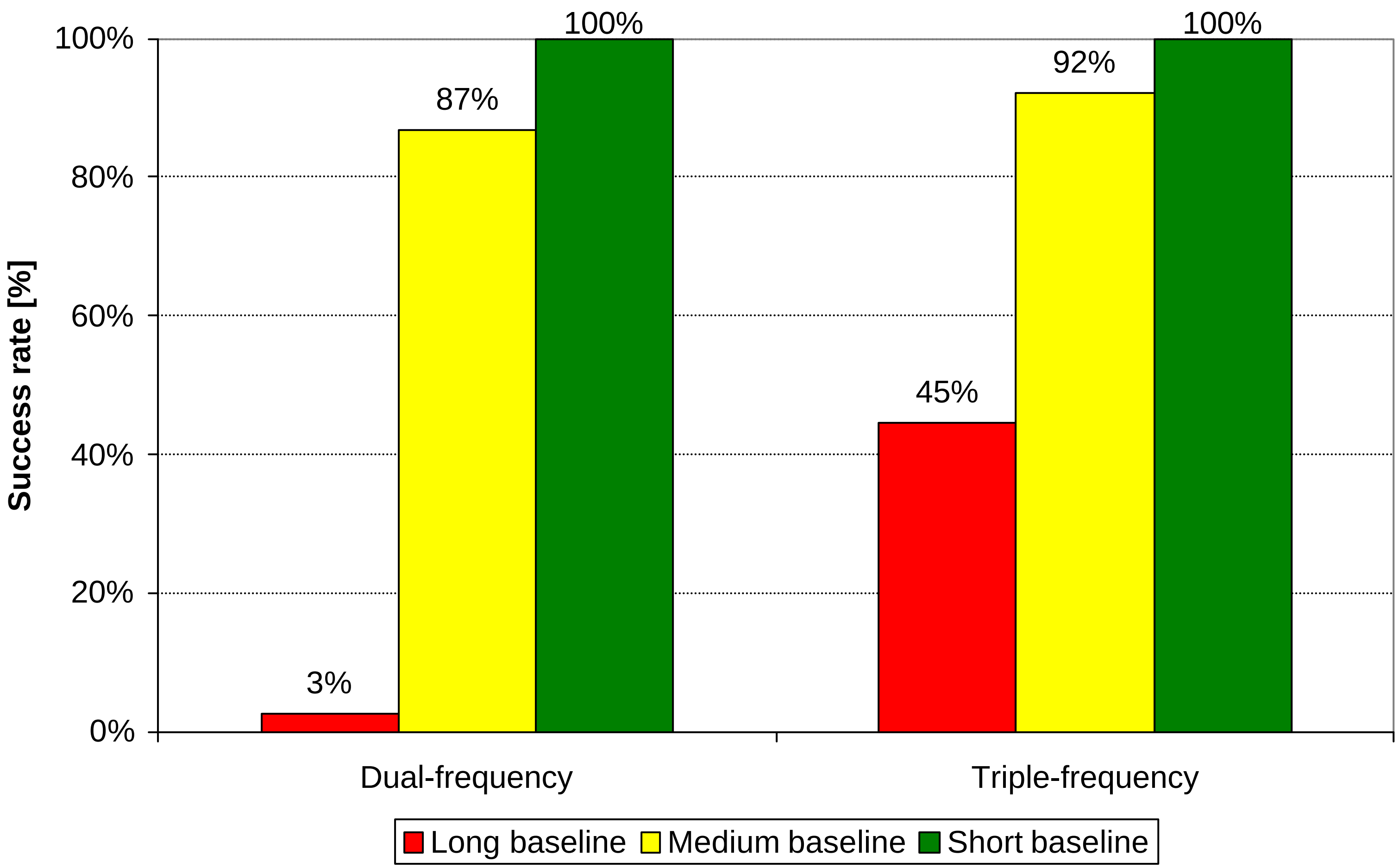


GPS only



Success rate [%]
100%
80%
60%
40%
20%
0%
0%
44%
100%
3%
57%
100%
Dual-frequency
Triple-frequency
Long baseline
Medium baseline
Short baseline

Integrated GPS and Galileo



Code observations - alternatives

Standard precision			
L1	0.30	E2-L1-E1	0.15
L5	0.10	E5b	0.10

High precision			
L1	0.30	E2-L1-E1	0.10
L5	0.05	E5b	0.05

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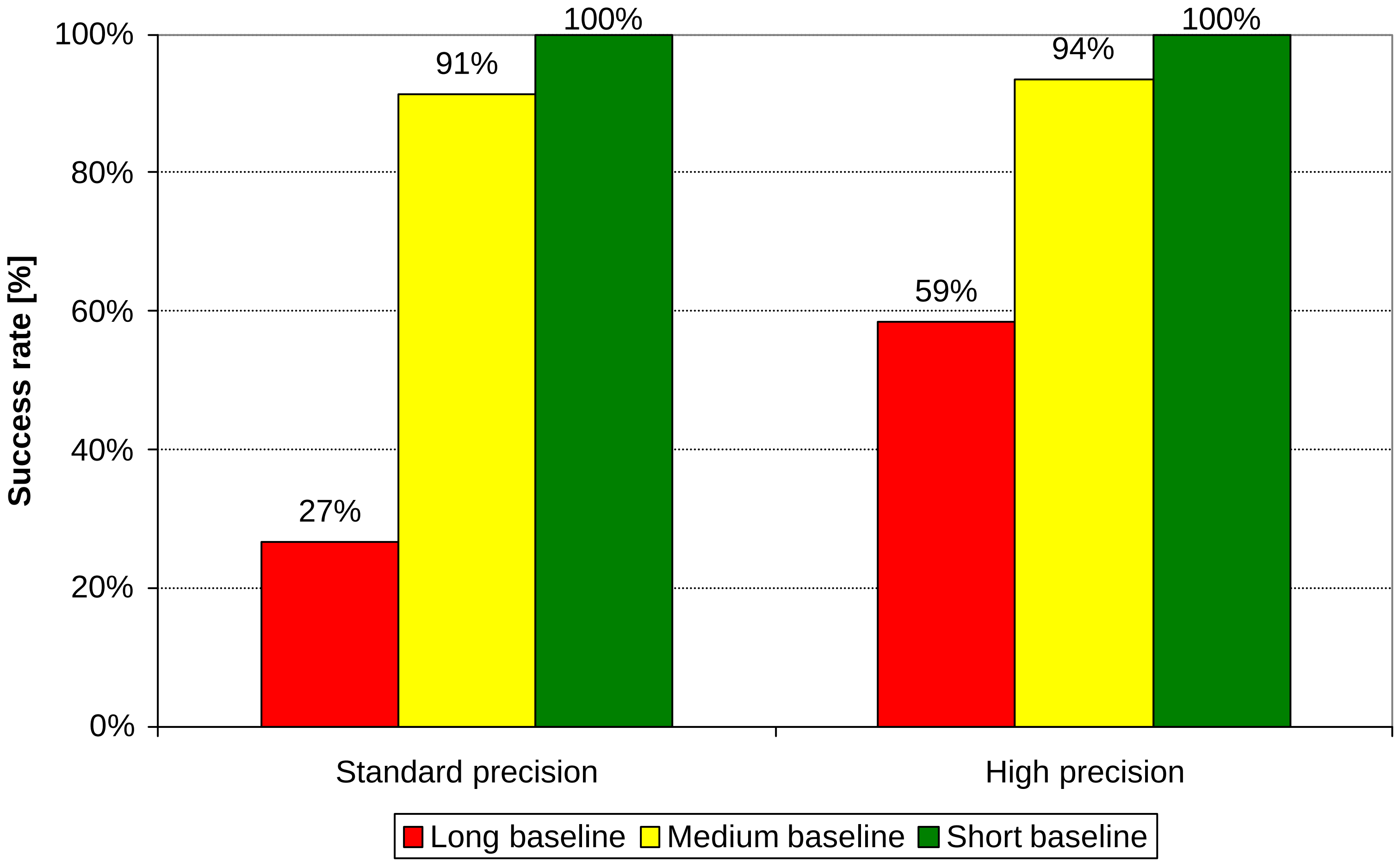
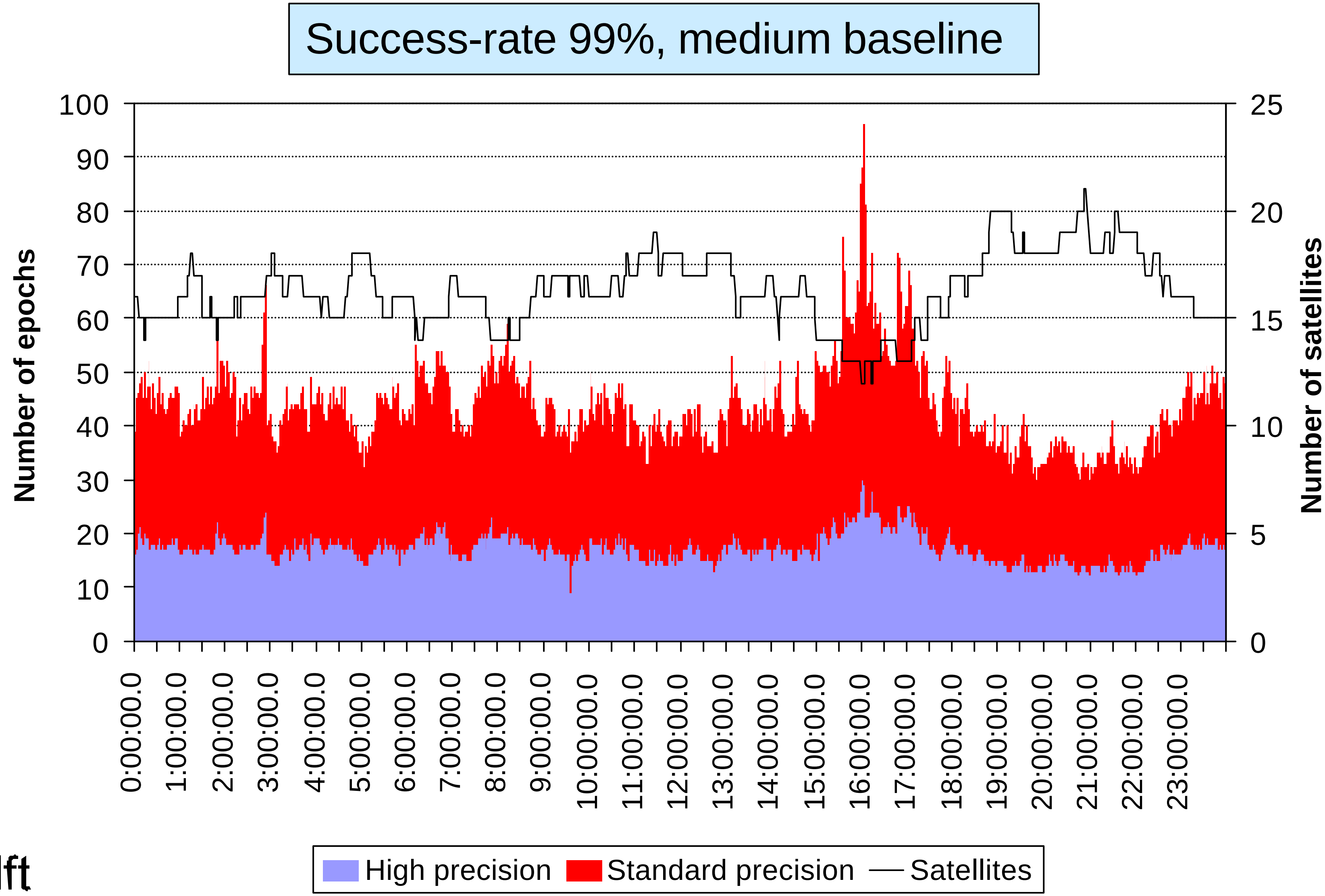
Integrated GPS and Galileo (2 freq.)



Integrated GPS and Galileo (2 freq.)



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Integrated GPS and Galileo

Integrated use of GPS and Galileo significantly increases ambiguity succes-rate

Single-epoch ambiguity resolution becomes feasible if ionospheric effects can be constrained

Very long-baseline ambiguity resolution requires more than one observation epoch and benefits most from triple-frequency integrated system

Major GNSS error sources

Ionosphere

Multipath

Ionosphere

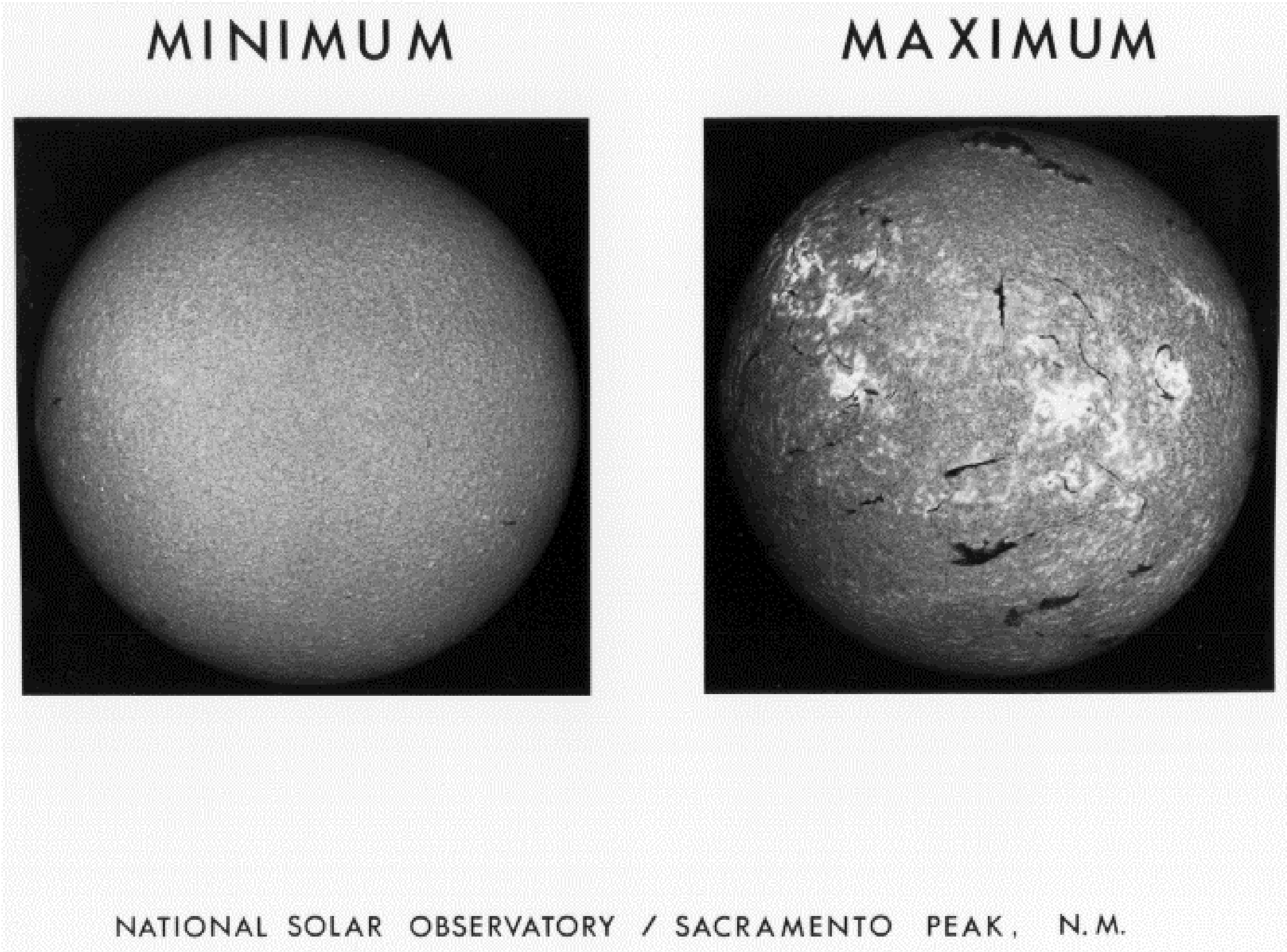
Ionosphere is dispersive: effect is frequency dependent

Effect depends on free electron density in atmosphere

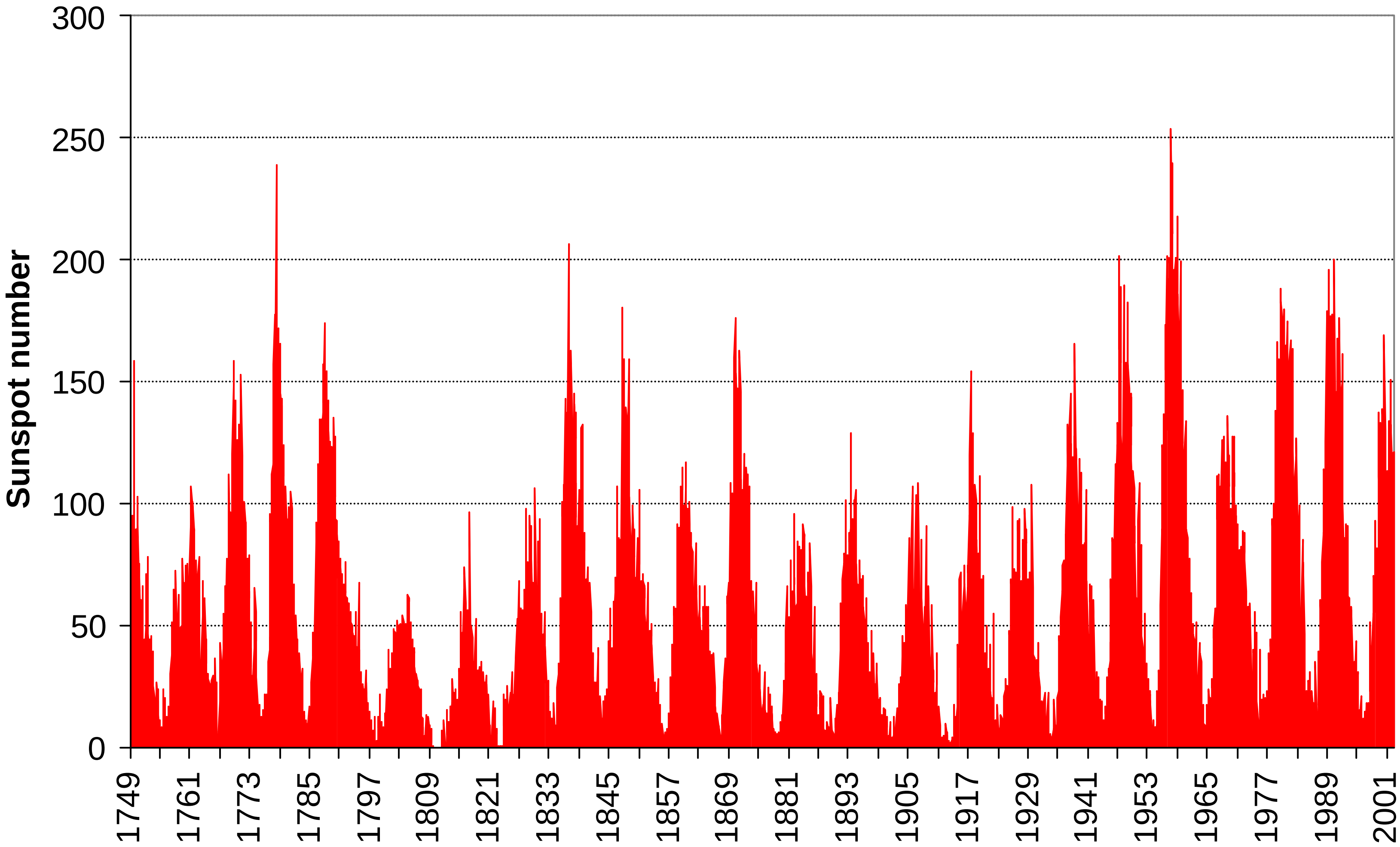
Electron density is related to solar activity

Solar activity has period of 11 years and is characterised by sunspot numbers

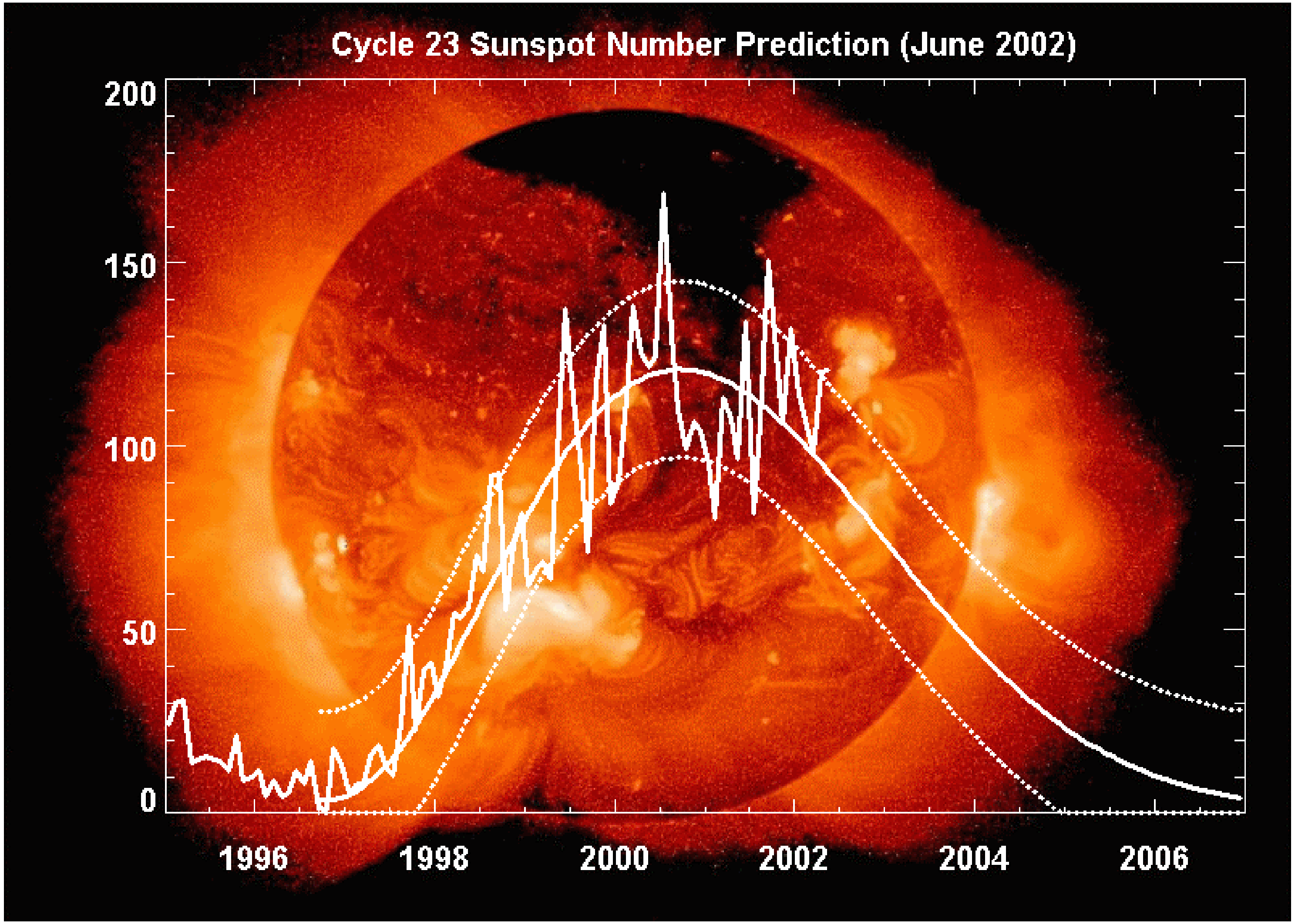
Sunspots


MINIMUM
MAXIMUM
NATIONAL SOLAR OBSERVATORY / SACRAMENTO PEAK, N.M.

Solar cycle and sunspot numbers



Sunspot number prediction



Effects of ionosphere

Poor GPS satellite tracking

Disturbance of GPS data links

Positioning biases

Incorrect ambiguity resolution
(also results in positioning biases)

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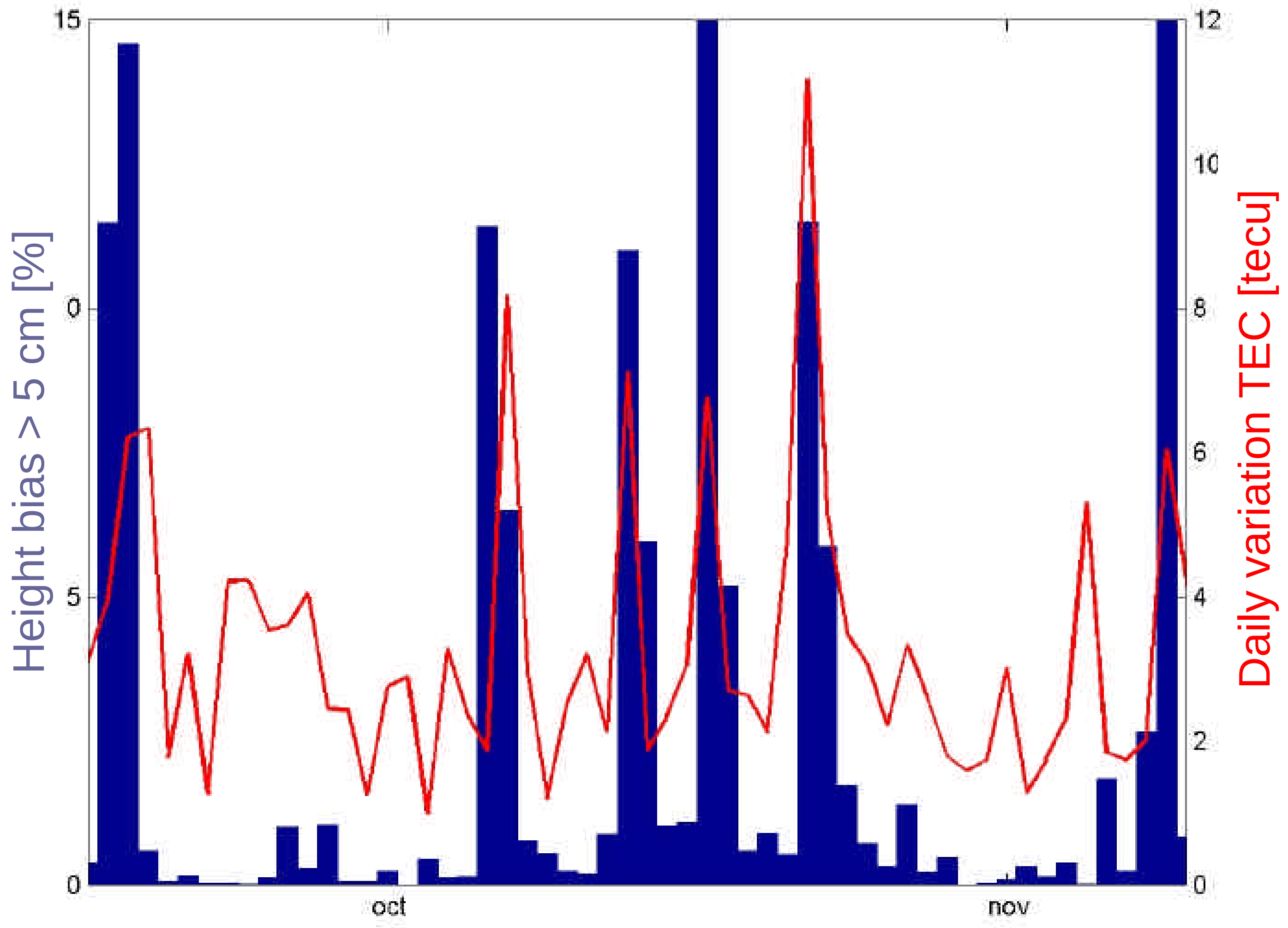
Ionosphere and positioning

Measurement set-up
Two permanent GPS receivers, 4 km apart (short baseline) in The Netherlands (52° N) Known baseline, continuously monitored

Ionosphere and positioning

Analysis procedure
Compute daily percentage of height errors greater than 5 cm for period of two months
Correlate this percentage to daily variations in Total Electron Content (TEC)

Height biases and TEC



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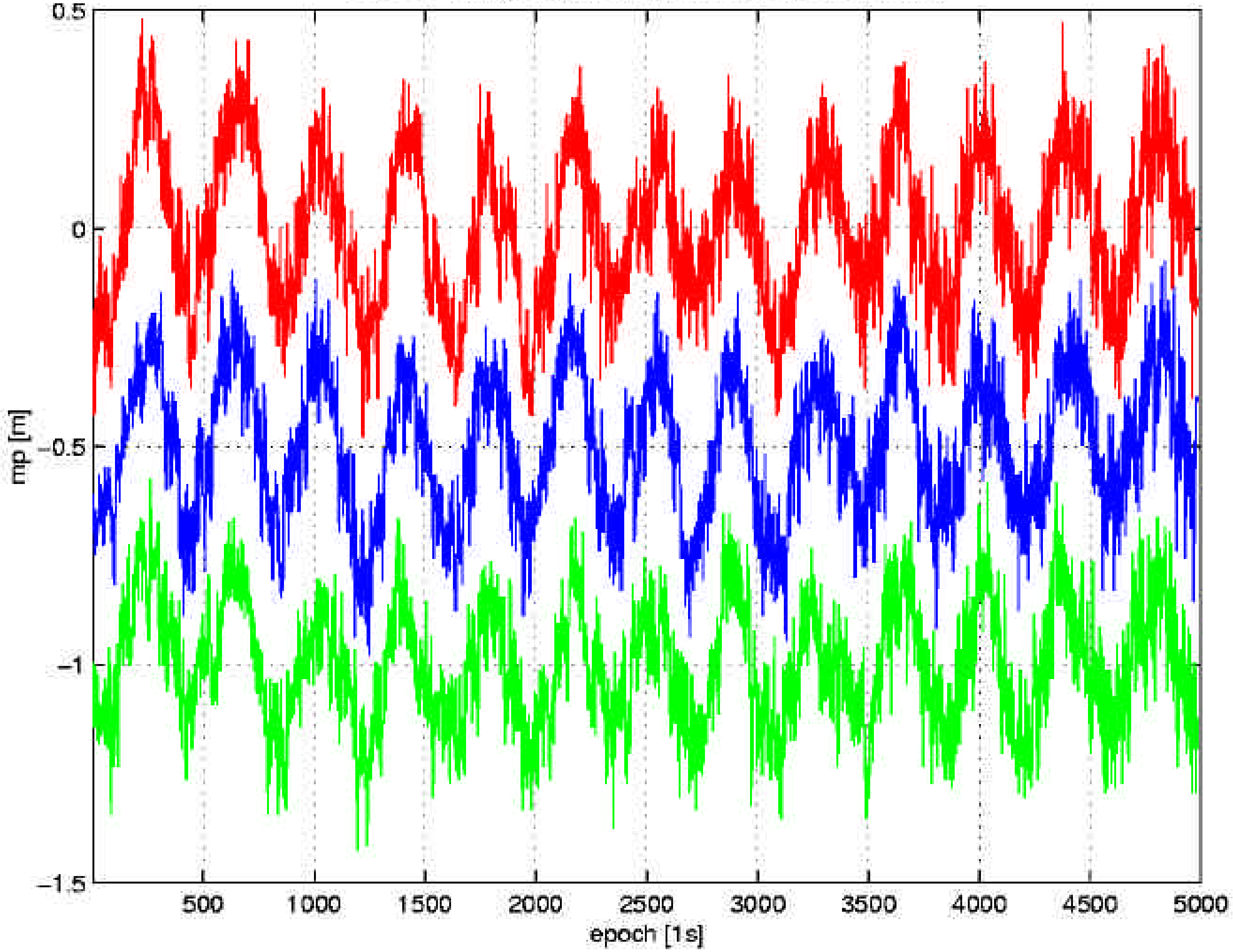
Effects due multipath

Periodic biases in
Observations Estimated positions (if same satellites are used)
Biases repeat every 23^h56^m

Multipath in observations

GPS SV06, L2-code



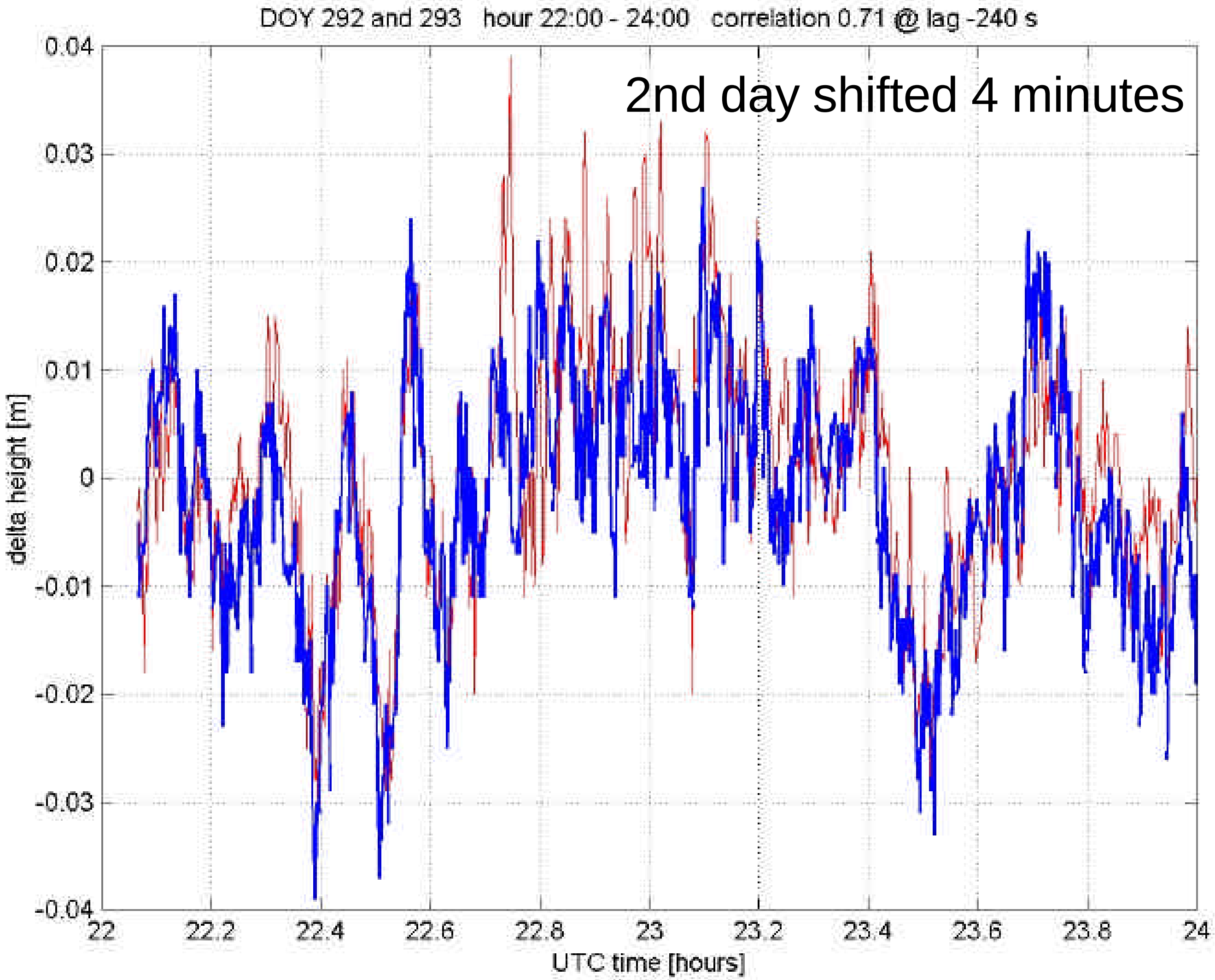
Multipath detection in positions

Aim
Show multipath explicitly in stationary baselines

Set-up
Collect data over 2×24 hours and determine presence of repeatable effects with period 23^h56^m

Background
GPS constellation has 23^h56^m repeatability ➡ satellite-reflector-antenna geometry re-occurs every day

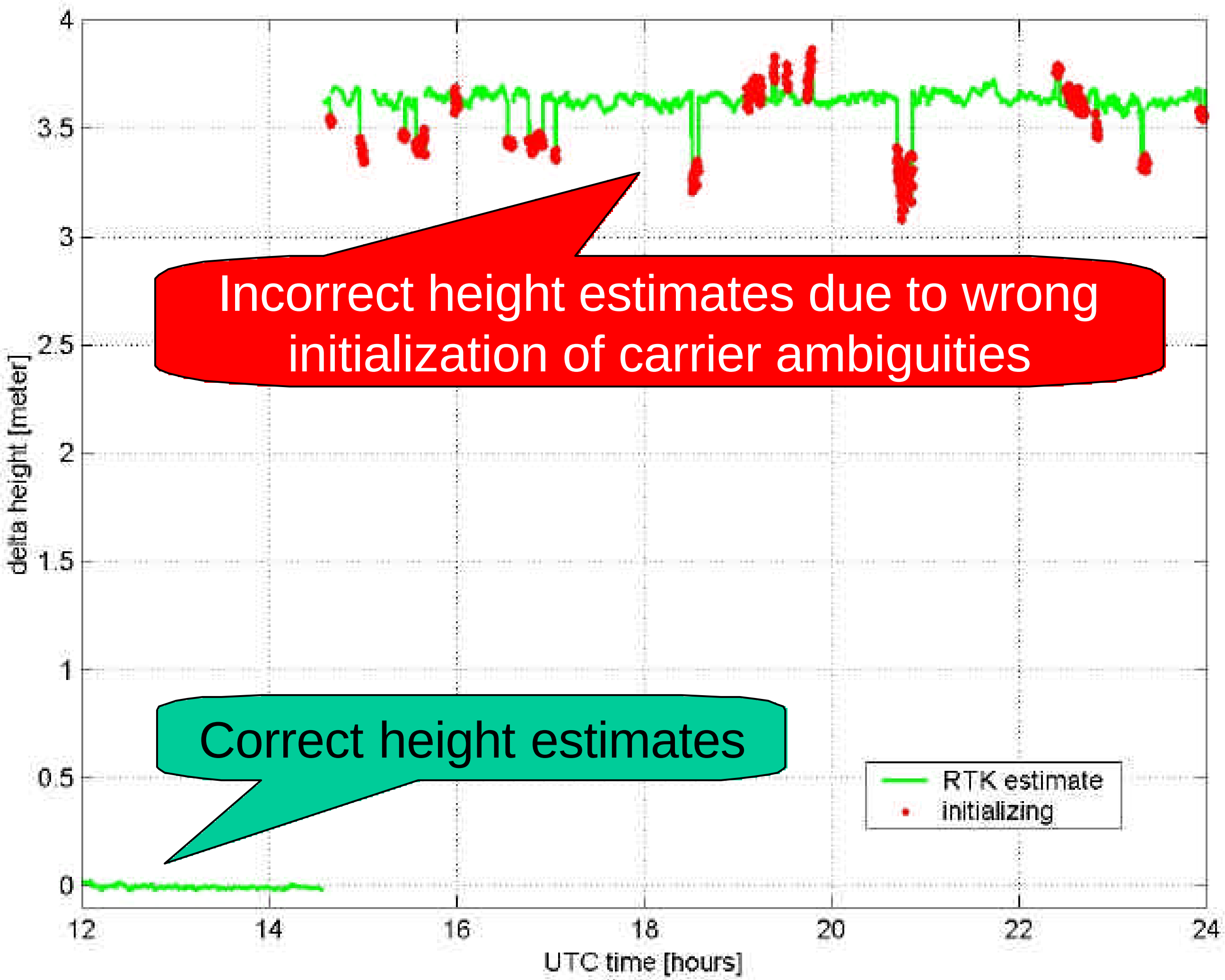
Height errors



Real-time kinematic (RTK) positioning

Ideal world
Centimeter accuracy in real-time, provided carrier ambiguities can be resolved to their correct integer values

RTK positioning in the real world



Precise RTK GNSS positioning

Choose reference stations carefully to avoid multipath as much as possible

Integrate RTK GPS with other sensors

Validate estimated carrier ambiguities

Trends in RTK positioning

From single-reference station to network-based RTK

Advantages
Higher reliability
Longer baselines
Less reference stations

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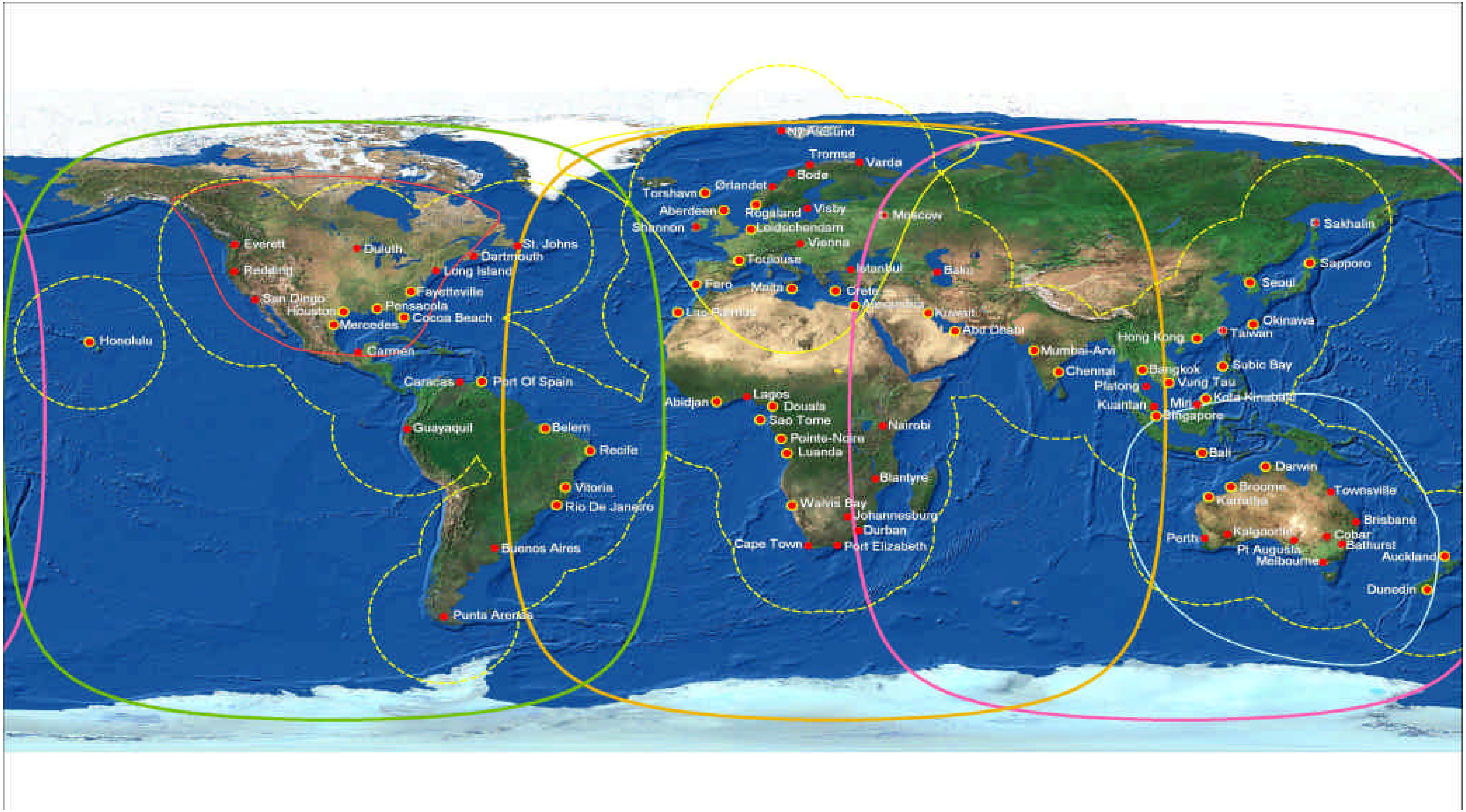
Fugro Starfix global DGPS network



Fugro Starfix HP

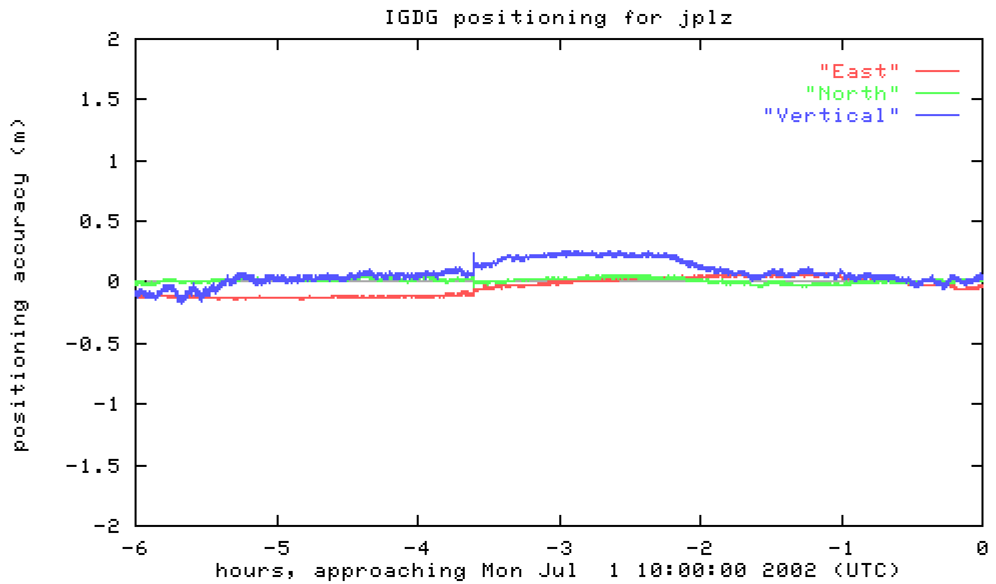
Starfix HP (High Performance)
Regional sub-networks of global Starfix network
Decimeter accuracy for distances up to 500 km

Jet Propulsion Laboratory's IGDG

Internet-based Global Differential GPS (IGSG)
Global network of reference stations
Reference station data collection via the Internet
Data dissemination to users via the Internet
Decimeter positioning accuracy

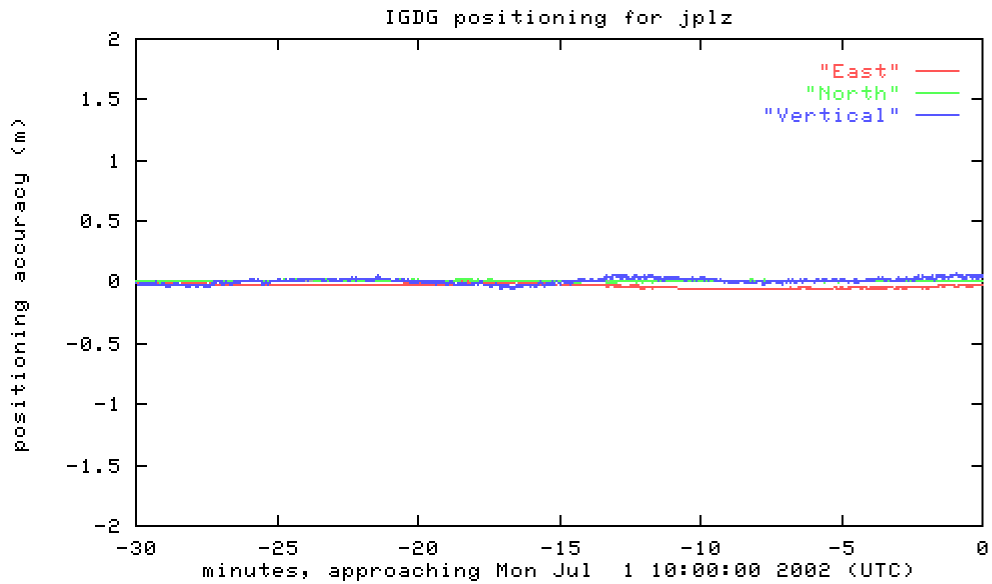
IGDG - demonstration results

See also http://gipsy.jpl.nasa.gov/igdg



Last six hours

Last 30 minutes



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Conclusions

Modernized GPS and future Galileo offer unprecedented accuracy and availability

Both systems are vulnerable to intentional and unintentional interference

Error sources (ionosphere, multipath) remain major concern

Network-based RTK will result in longer baseline lengths and less reference stations