TECHNISCHE UNIVERSITÄT WIEN

Visibility study of Galileo satellites from a VLBI network

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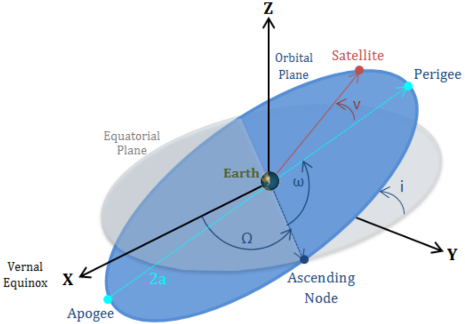
Satellite observations with VLBI

- observations to quasars are integral part of VLBI
- VLBI transmitter on satellites would enable observing satellites with VLBI telescopes
- observations to satellites
  - enable interesting scientific applications
  - place new requirements

$\rightarrow$ newly developed satellite scheduling module in VieSched++

Satellite observations with VLBI **Applications**

- geodetic space ties for connecting reference frames
- improvement of geodetic products, in terms of ITRF
- determination of absolute orientation of satellite constellation → Right Ascension of Ascending Node (Ω)

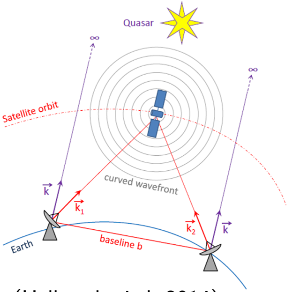


www.gsc-europa.eu

Satellite observations with VLBI

Requirements

- cross-eyed observation geometry
- satellite is moving while observing → antenna has to follow
- conditions have to be checked continuously during a scan
  - visibility (horizon mask)
  - antenna slew rates
  - sun distance
  - cable wrap

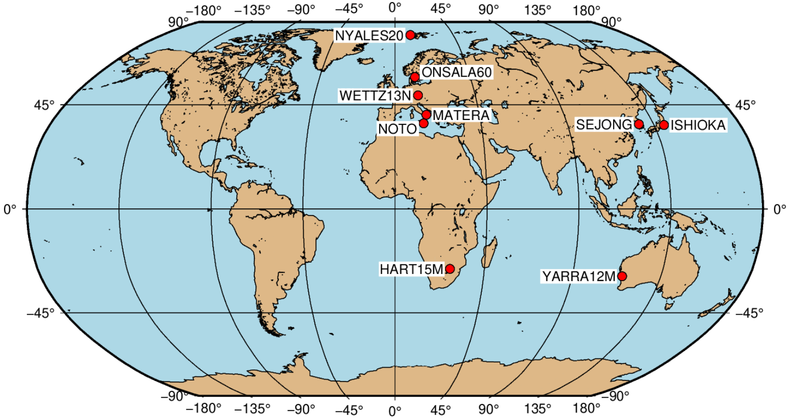


(Hellerschmied, 2014)

Visibility study of Galileo satellites

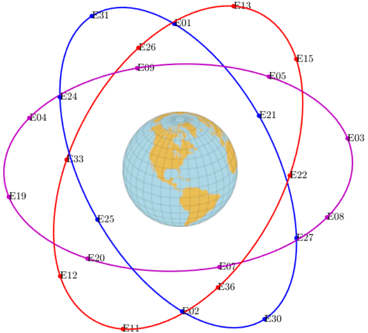
- 24 - hour IVS - R1978 session
- December 21, 2020 00:00 UTC
- 9 station network
- satellite scheduling module of VieSched++ was used to determine all possible observations to Galileo satellites
- observations are evaluated through
  - visibility (number of stations)
  - observation geometry

VLBI network



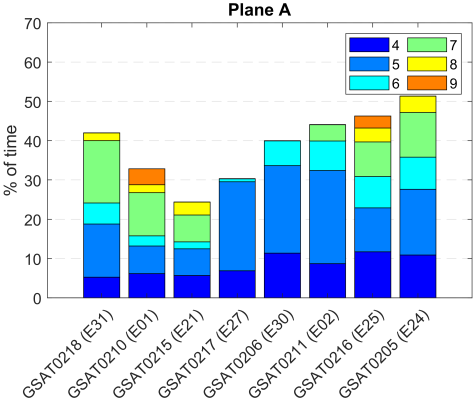
Galileo satellite system

- 24 satellites[1]
- Medium Earth Orbit (MEO) in 23.222 km altitude
- three orbital planes (A, B and C) $\rightarrow$ spaced by 120°
- inclination of 56°
- eight satellites in each plane
  $\rightarrow$ angular distance of 45°
- ground track repeat period
  of 10 days



[1] considering the current number of active satellites

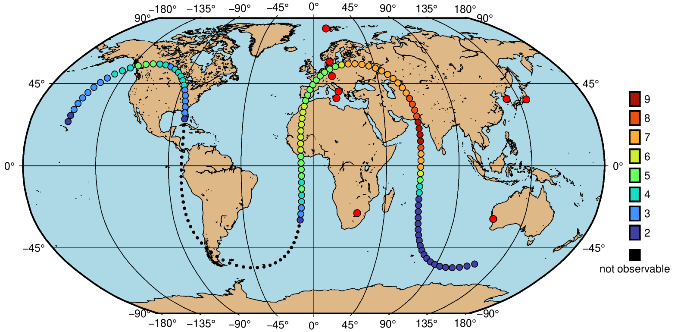
Visibility in percent



Percentage of time the satellites in Plane A, ordered by their slot number, are observable during the 24-hour IVS-R1978 session on December 21, 2020, color-coded by the number of stations from which the satellite is observable. A cut-off elevation angle of five degrees is considered.

Visibility GSAT0216 (E25)

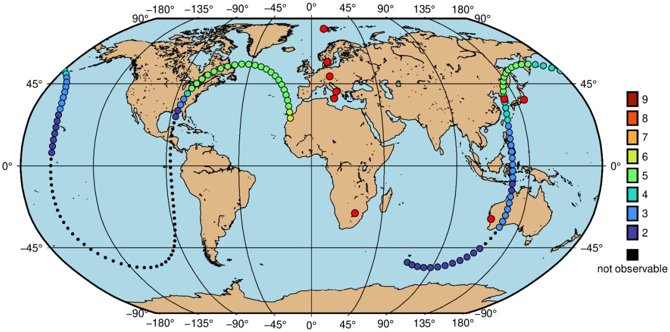
- rather high visibility due to course of ground track



Ground track of GSAT0216 (E25) during the 24-hour IVS-R1978 session on December 21, 2020. The dots represent the position of the satellite over Earth in a ten minute interval color-coded by the number of stations from which the satellite is visible. The smaller black dots represent positions where the satellite is not visible from at least two stations.

Visibility GSAT0217 (E27)

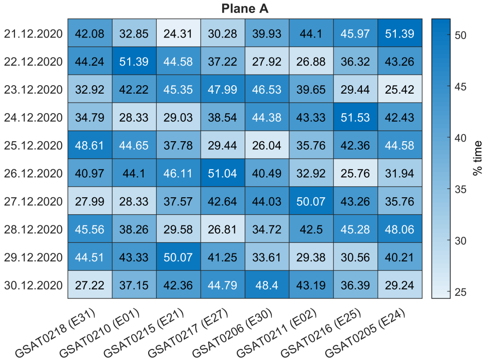
- rather low visibility due to course of ground track



Ground track of GSAT0217 (E27) during the 24-hour IVS-R1978 session on December 21, 2020. The dots represent the position of the satellite over Earth in a ten minute interval color-coded by the number of stations from which the satellite is visible. The smaller black dots represent positions where the satellite is not visible from at least two stations.

Visibility over repeat period

- visibility of satellites is changing from day to day



Percentage of time the satellites in Plane A, ordered by their slot number, are observable from at least four stations over a period of 10 days starting on December 21, 2020. A cut-off elevation angle of five degrees is considered.

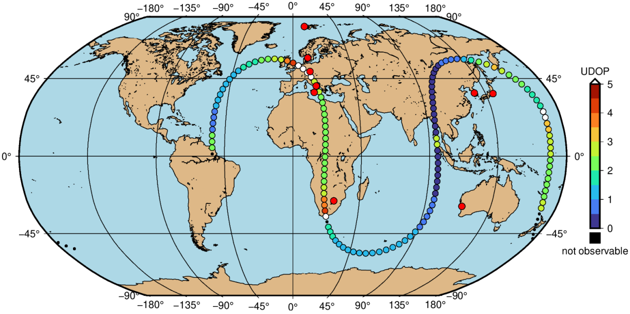
Observation geometry

- precision of UT1-UTC depends on observation geometry
- UT1-UTC Dilution of Precision factor as indicator for sensitivity of satellite observation to UT1-UTC
- low UDOP factor means
  - better observation geometry
  - observation is more sensitive to UT1-UTC

$\rightarrow$ see Appendix

Observation geometry GSAT0102 (E12)

- low UDOP, if visible for stations forming E-W baselines
- high UDOP, if visible for stations forming N-S baselines



Ground track of GSAT0102 (E12) during the 24-hour IVS-R1978 session on December 21, 2020. The dots represent the position of the satellite over Earth in a ten minute interval color-coded by the values of the UDOP factor. The smaller black dots represent positions where the satellite is not visible from at least two stations.

Summary

- satellite observations provide new possibilities
- no difference of visibility of the
  - three orbital planes
  - satellites within the plane
- visibility and observation geometry depends on
  - distribution of observing stations
  - session time
- Galileo exhibit high visibility

References

- Belli, F. (2020). *Transfer of absolute orientation to Galileo orbits with VLBI*, Master thesis, Technical University of Munich.
- Hellerschmied, A. (2014). *Observations of GNSS satellites with VLBI antennas - From observation planning to practical implementation*, Master thesis, Technical University of Vienna.
- Wolf, H. (2021). *Satellite Scheduling with VieSched++*, Master thesis, Technical University of Vienna.
- Schartner, M. & Böhm J. (2019). *VieSched++: A New VLBI Scheduling Software for Geodesy and Astrometry*, PASP 131(1002):084501, doi: https://doi.org/10.1088/1538-3873/ab1820
- VieSched++: https://github.com/TUW-VieVS/VieSchedpp/

Appendix

UT1 - UTC Dilution of Precision

$$A = \begin{pmatrix} \frac{\delta \Delta \tau_1}{\delta UT1} \\ \vdots \\ \frac{\delta \Delta \tau_n}{\delta UT1} \end{pmatrix}$$

$$N = A^T A = \left(\frac{\delta \Delta \tau_1}{\delta UT1}\right)^2 + \cdots + \left(\frac{\delta \Delta \tau_n}{\delta UT1}\right)^2$$

- A as design matrix
- $\Delta \tau_i$ as observed delay of reception times of two stations
- $\frac{\delta \Delta \tau_i}{\delta UT1}$ as partial derivative of $\Delta \tau_i$ with respect to UT1

UT1 - UTC Dilution of Precision

- UDOP factor as square root of trace of cofactor matrix Q_{xx}
- sensitivity of VLBI observations to satellites to UT1-UTC (Belli, 2020)

$$Q_{xx} = N^{-1} = \frac{1}{\left(\frac{\delta \Delta \tau_1}{\delta UT1}\right)^2 + \cdots + \left(\frac{\delta \Delta \tau_n}{\delta UT1}\right)^2}$$

$$UDOP = \sqrt{\frac{1}{\left(\frac{\delta \Delta \tau_1}{\delta UT1}\right)^2 + \cdots + \left(\frac{\delta \Delta \tau_n}{\delta UT1}\right)^2}}$$

UT1 - UTC Dilution of Precision (Belli, 2020)

- a_k represents an entry in the design matrix for one baseline

$$a_k = \vec{e}_3 \cdot \left(\frac{\vec{y}}{R} \times \left(\frac{\vec{R}_1}{\rho_1} - \frac{\vec{R}_2}{\rho_2}\right)\right)$$

  - $\vec{R}_1$ and $\vec{R}_2$ as position vectors of the two VLBI antennas forming the baseline
  - $\vec{y}$ as position vector of satellite in the Earth-fixed frame
  - $\rho_i = \|\vec{y} - \vec{R}_i\|$ as range from each station to the satellite
  - R as Earth radius
  - $\vec{e}_3$ as unit vector in z-direction
- a_k represents the sensitivity of the range difference $\Delta\rho$ to the Earth rotation angle
  - $\Delta\rho = \rho_1 - \rho_2$ as difference between the ranges from two stations, forming a baseline, to the satellite

UT1 - UTC Dilution of Precision (Belli, 2020)

- UDOP factor as square root of trace of cofactor matrix Q_{xx}

$$UDOP = \frac{1}{\sqrt{{a_1}^2 + {a_2}^2 + \cdots + {a_n}^2}}$$

  - a_k with $k = 1, 2, ...n$ represents entries in design matrix for n baselines

- low UDOP factor $\rightarrow$ satellite observation is more sensitive to observe UT1-UTC

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