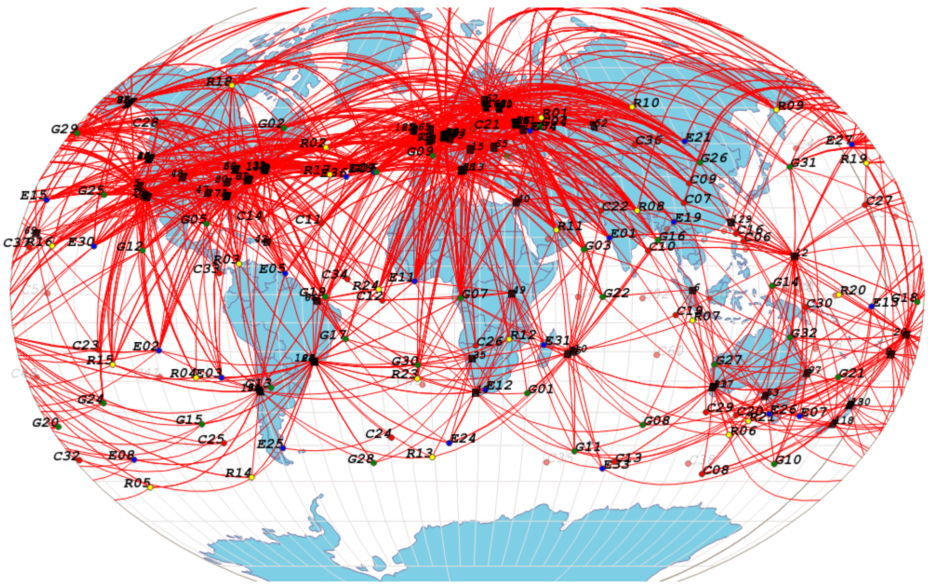
The *unofficial* Galileo Weekly Performance Report
Sat, 28 Nov 2020 23:59:42 +0000 - Sat, 05 Dec 2020 23:59:42 +0000
(WN 1110)

The galmon.eu project



Monday 7th December, 2020

contact: bert@hubertnet.nl

Abstract

This week saw the unexpected entry into service of E14 and E18, which are now known as the 'auxiliary' satellites.

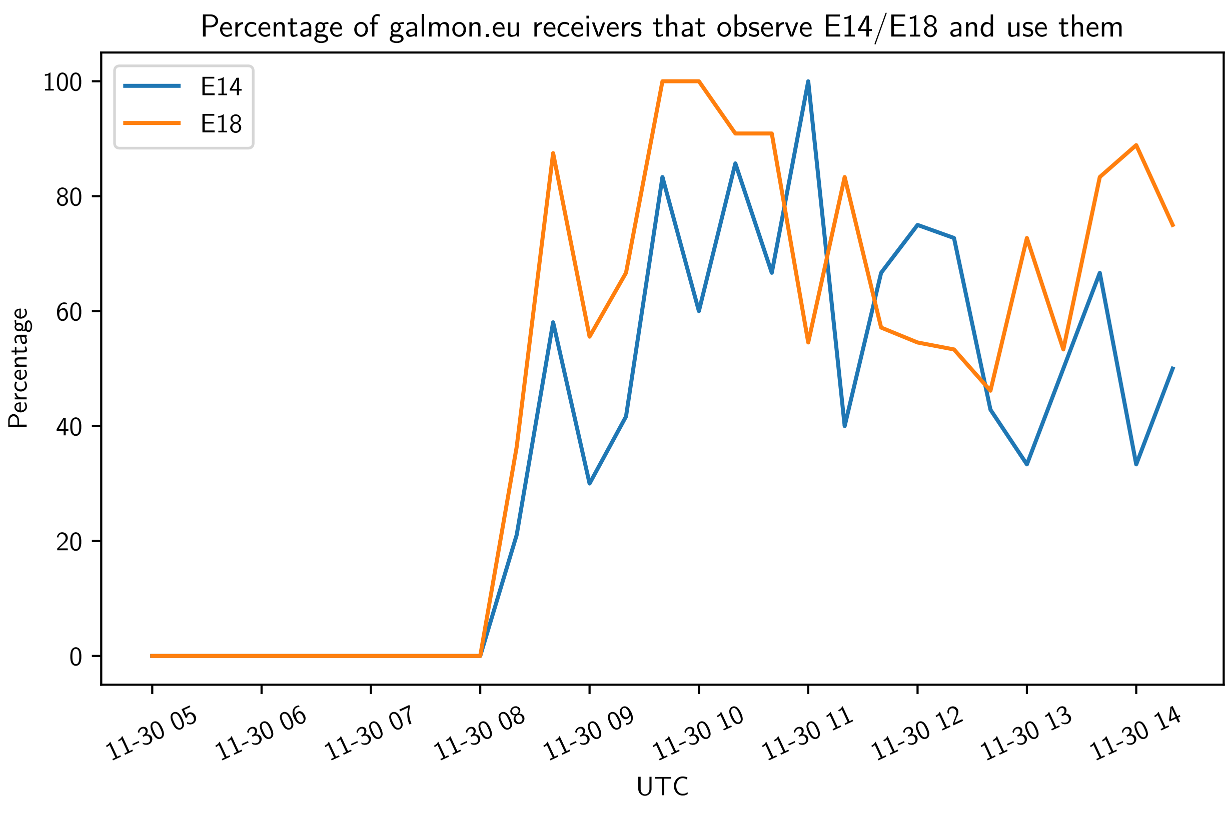
In addition, this week delivered improved Galileo uplink station capacity, with the number of dishes observed rising from 14 to 17. But availability has not been perfect, and a number of satellites have served 'ripe' or even too old data (E14, E18).

In a separate blog post I will write on why the unexpected advent of E14 and E18, which have special orbits that deviate substantially from normal GNSS orbits, was somewhat upsetting.

The good news is that the new satellites are contributing to improved performance, both in terms of coverage and in terms of a higher percentage of the Earth's surface achieving good PDOP numbers.

In section 7.1 we observe a clear step change improvement around the time of entry into service of E14 and E18 (around 08:30 UTC on Monday the 30th of November). New in this report are coverage and PDOP measures for 20-degree+ elevation satellites, representing 'city' users. This is not part of the Galileo Minimum Performance Levels, but it does matter.

In this graph, we can see that at least Ublox chipsets immediately started making good use of the new auxiliary satellites:



In a new Galileo Service Notice we can read that E14 and E18, occupying eccentric orbits, are a "nice to have" addition to the Galileo constellation. In short, if one of the new auxiliary satellites is unavailable, this does not represent a breach of the Galileo Minimum Performance Levels.

However, as long as the satellites work, they do count towards the MPLs for PDOP, coverage etc.

Because of this, in the report, we'll now take E14 and E18 more seriously. In some graphs we had removed the two eccentric satellites because they would often ruin graphs by showing significant orbit errors, far larger than the other satellites. There are now dedicated graphs for E14 and E18 so we can see how well they are doing.

This week, on average 0.0% of the earth's surface violated the PDOP performance level for 5 degree elevation satellites, while 0.4% was violated for 10 degree elevation. See 1.2 for finer definitions of these metrics.

See chapter 2 for further details.

Contents

Chapter 1

Introduction

The galmon.eu project strives to publish a weekly unofficial Galileo Performance Report every week. In good weeks, this report will have been processed manually, removing measurement anomalies and other oddities. If we are too busy, there will be an automated report that might for example show bad behaviour of satellites undergoing planned maintenance.

Automated reports will clearly be flagged as such.

Despite this, it should be noted that even manually processed reports only show what we can see. If we report on a problem, it is entirely possible we are misunderstanding a situation.

In addition, even when we show problems for individual Galileo satellites, this in no way means Galileo performance was impaired. We have separate graphs for that.

Finally, we do report on global metrics such as "x% of the Earth's surface not having Galileo coverage, as defined by being able to see 4 satellites more than 5 degrees above the horizon".

These metrics are defined in the Galileo Service Definition Document, but the SDD also states that the defined Minimum Performance Level is not breaching such a metric for more than 7 days in a row.

Our reports only talk about instantaneous breaches of such performance levels. Readers can determine for themselves if a 6 day breach of a performance level also constitutes a breach of the Minimum Performance Levels.

Official Galileo Performance Reports are published on the site of the Galileo Service Centre.

1.1 Intended use

These reports are provided in the hope that these will be useful for the Galileo project. The same goes for our live dashboard on `https://galmon.eu`.

If anything in these reports is found to be incorrect, or in need of explanation, feedback is most welcome (bert@hubertnet.nl). Similarly, suggestions for additional graphs or metrics are much appreciated.

1.2 Performance levels

As noted, the Galileo SDD contains many performance definitions. We try to align to metrics also present in the SDD, but also provide additional numbers that may be more operationally relevant on a per-week basis.

The SDD defines a Positional Dilution of Precision (PDOP) of more than 6.0 as a performance level threshold, measured for a receiver able to see satellites more than 5 degrees above the horizon.

In addition, the SDD requires visibility of 4 or more satellites more than 5 degrees above the horizon.

Beyond the SDD's 5 degree limit, we also report on a more realistic 10 degree limit (which is closer to what users would encounter).

Galileo currently has a constellation of 22 healthy satellites. This is two less than the design, but for reporting purposes, we consider 22 to be the nominal constellation size.

1.3 Data sources, acknowledgments

This report is based on many data sources, and we are very grateful for all the data that is being made public. Such transparency enables great reporting.

We specifically acknowledge the following great data sources:

- DLR and Spaceopal provide a realtime RTCM State Space Representation feed, which we use to plot orbit errors
- CNES provides a similar but independent feed, which makes it possible to separate measurement problems from Galileo problems
- GFZ Potsdam provides excellent post-processed orbit data (SP3) which provide even more authoritative orbit data
- ESA/ESOC provides similar data, calculated independently
- The International GNSS Service (IGS) who distribute and coordinate a vast network of files and realtime streams
- The galmon.eu volunteer receiver network, using over 80 stations around the world to receive each and every Galileo (and BeiDou, GLONASS and GPS) message

Galmon.eu would not be possible without the many many volunteer station operators around the world.

In addition, we thank the Galileo Service Centre and the Spaceopal NAVCAST helpdesks for patiently answering our many questions.

We also thank the European Commission's Joint Research Centre for authoring the NeQuick G model used in this report.

Finally, a large cast of mostly anonymous engineers, researchers, scientists, operators and Galileo customers have provided very valuable insights that made this report possible, and hopefully useful.

1.4 About us

We are an independent project, not affiliated with any Galileo vendor or organization.

The galmon.eu network is described in this post by Bert Hubert.

A presentation about our technologies is here.

The source code to our project can be found on GitHub.

Chapter 2

Weekly summary & open items

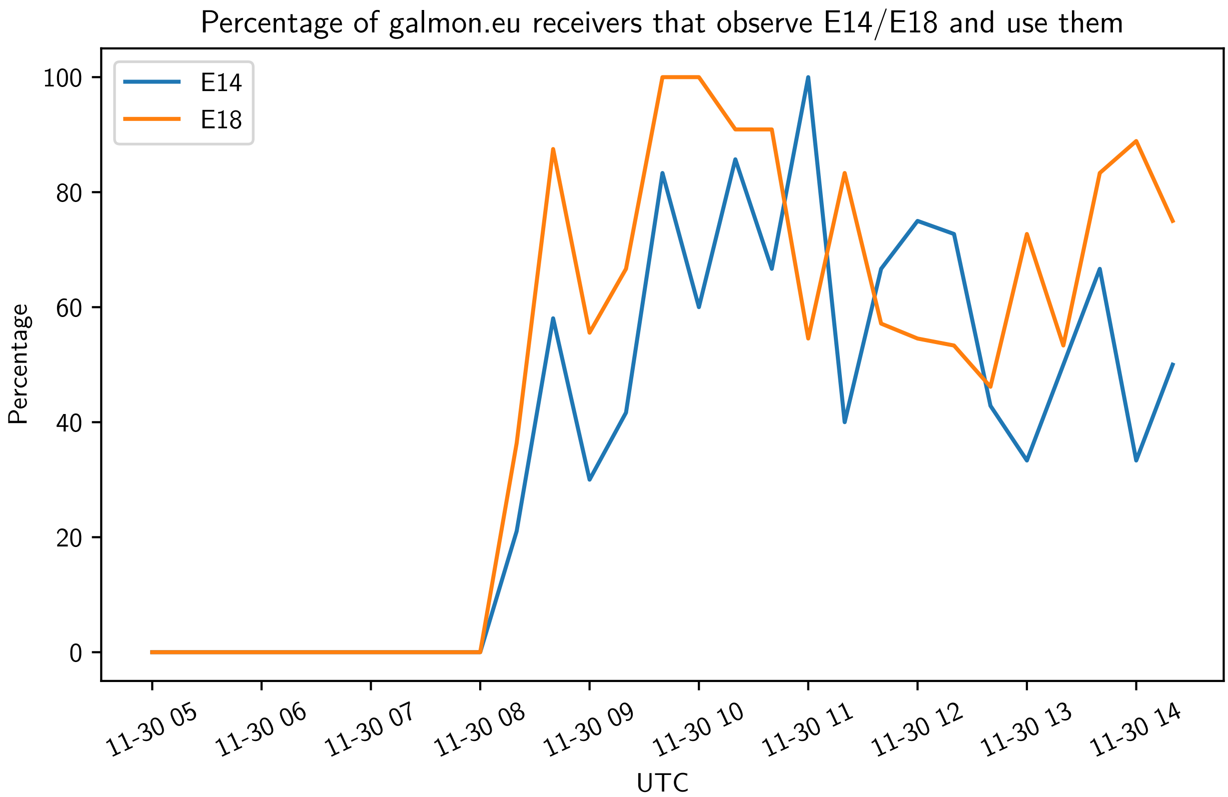
This week saw the unexpected entry into service of E14 and E18, which are now known as the 'auxiliary' satellites.

In addition, this week delivered improved Galileo uplink station capacity, with the number of dishes observed rising from 14 to 17. But availability has not been perfect, and a number of satellites have served 'ripe' or even too old data (E14, E18).

In a separate blog post I will write on why the unexpected advent of E14 and E18, which have special orbits that deviate substantially from normal GNSS orbits, was somewhat upsetting.

In section 7.1 we observe a clear step change improvement around the time of entry into service of E14 and E18 (around 08:30 UTC on Monday the 30th of November). New in this report are coverage and PDOP measures for 20-degree+ elevation satellites, representing 'city' users. This is not part of the Galileo Minimum Performance Levels, but it does matter.

In this graph, we can see that at least Ublox chipsets immediately started making good use of the new auxiliary satellites:



In a new Galileo Service Notice we can read that E14 and E18, occupying eccentric orbits, are a "nice to have" addition to the Galileo constellation. In short, if one of the new auxiliary satellites is unavailable, this does not represent a breach of the

Galileo Minimum Performance Levels.

However, as long as the satellites work, they do count towards the MPLs for PDOP, coverage etc.

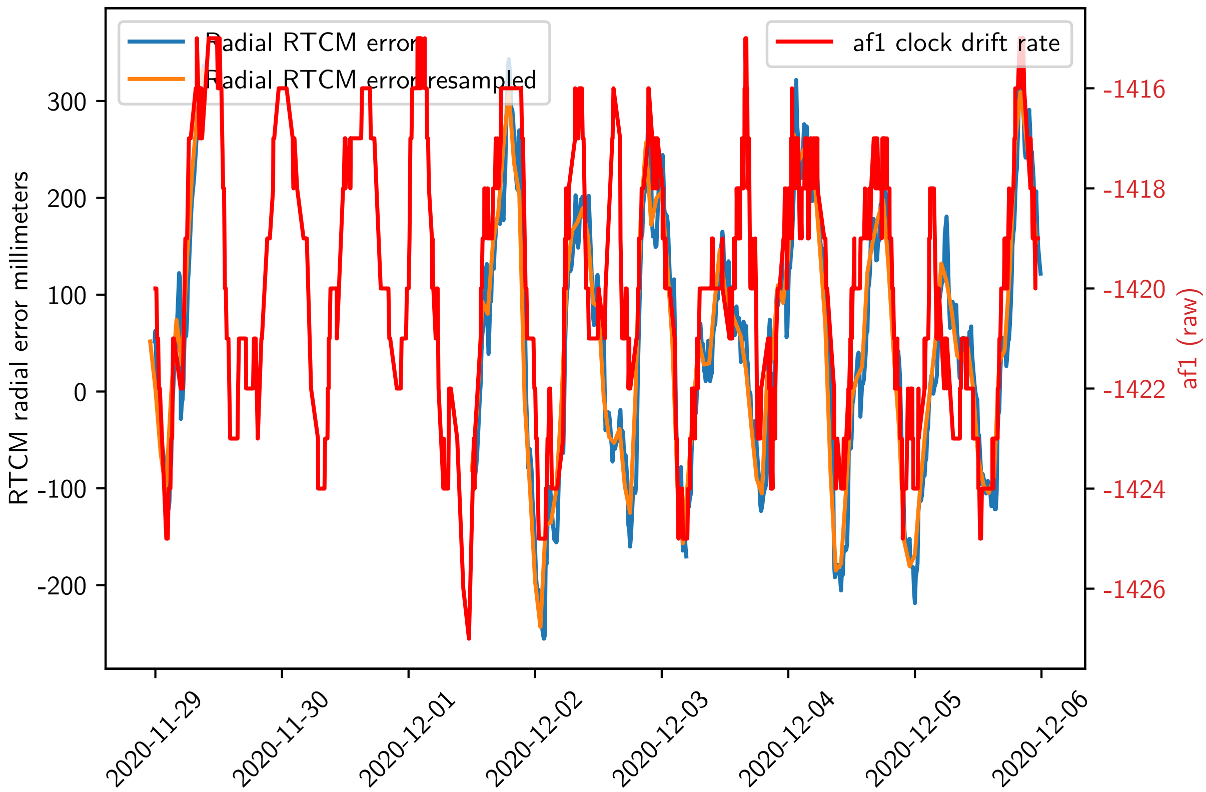
Because of this, in the report, we'll now take E14 and E18 more seriously. In some graphs we had removed the two eccentric satellites because they would often ruin graphs by showing significant orbit errors, far larger than the other satellites. There are now dedicated graphs for E14 and E18 so we can see how well they are doing.

This week, on average 0.0% of the earth's surface violated the PDOP performance level for 5 degree elevation satellites, while 0.4% was violated for 10 degree elevation. See 1.2 for finer definitions of these metrics.

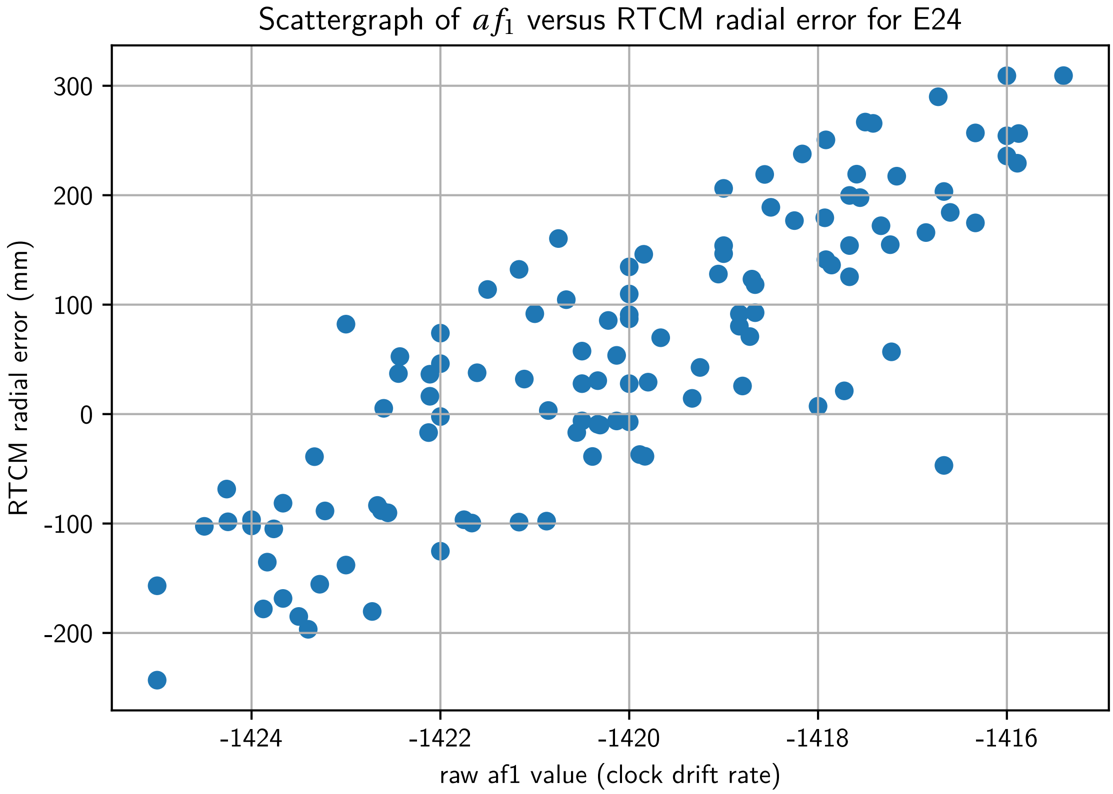
2.1 Ongoing oscillatory oddity

As observed in the rest of this report, most measured errors show an oscillation with a period that seems similar to the Galileo orbital period.

Here is a graph of the E24 RTCM radial error (left axis) and the raw af_1 clock drift parameter (right axis).



There appears to be a strong correlation between these two metrics:



This correlation is strong enough that Galileo orbit errors can meaningfully be improved by applying a correction based on the reported af_1. We also observe however that there is a corresponding and inverse signal in the clock error. As such the impact on the SISE (see below) is not as pronounced.

The oscillation may indicate a transfer of uncertainty from the space to the time component.

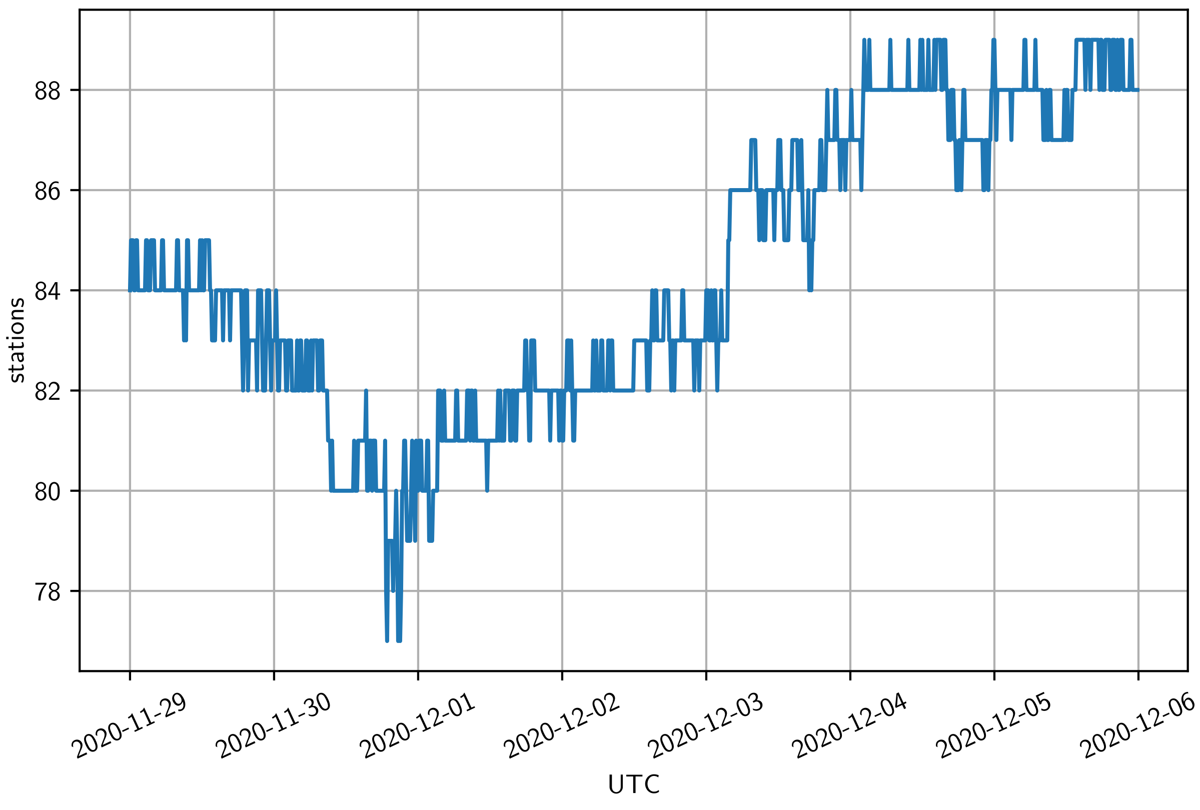
Chapter 3

Availability

3.1 The galmon.eu network

Nominally there are around 85 stations active in the galmon.eu network. Because many of our stations are in faraway places, connectivity and power sometimes suffer. This graph shows if we had any problems over the reporting period.

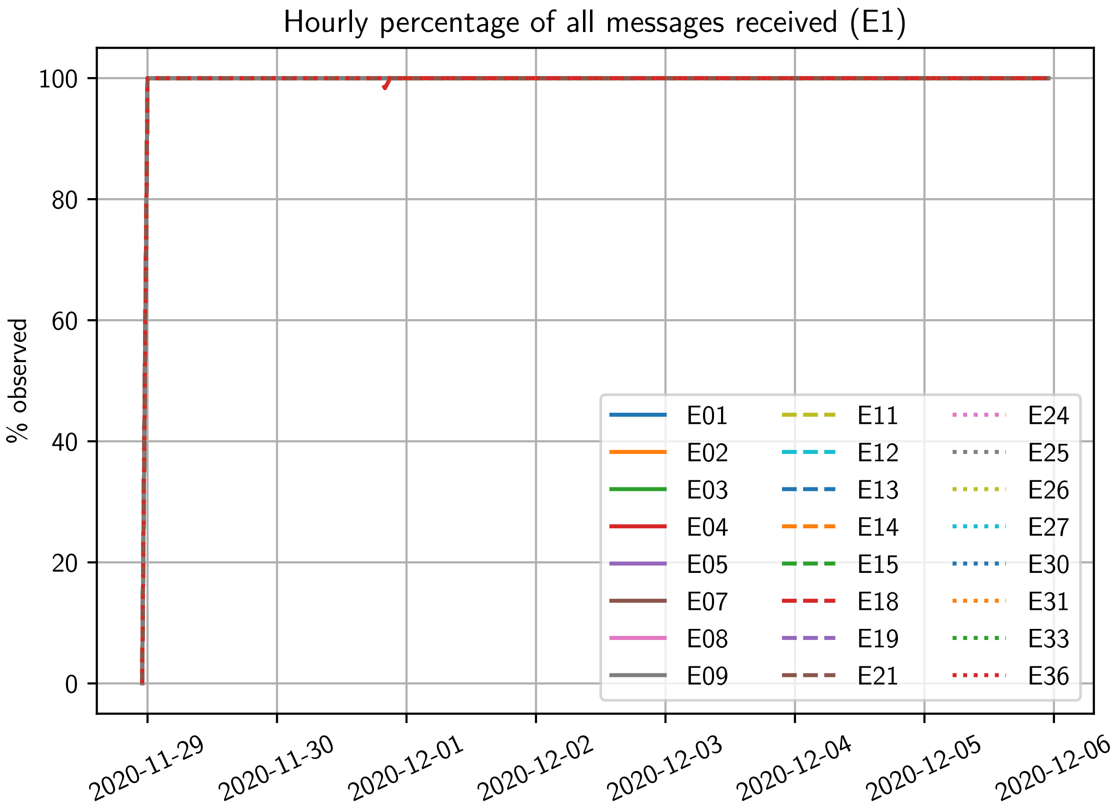
Note that most stations only see the E1 band, some see E5b and one sees E5a and E6. We're working on expanding this coverage.



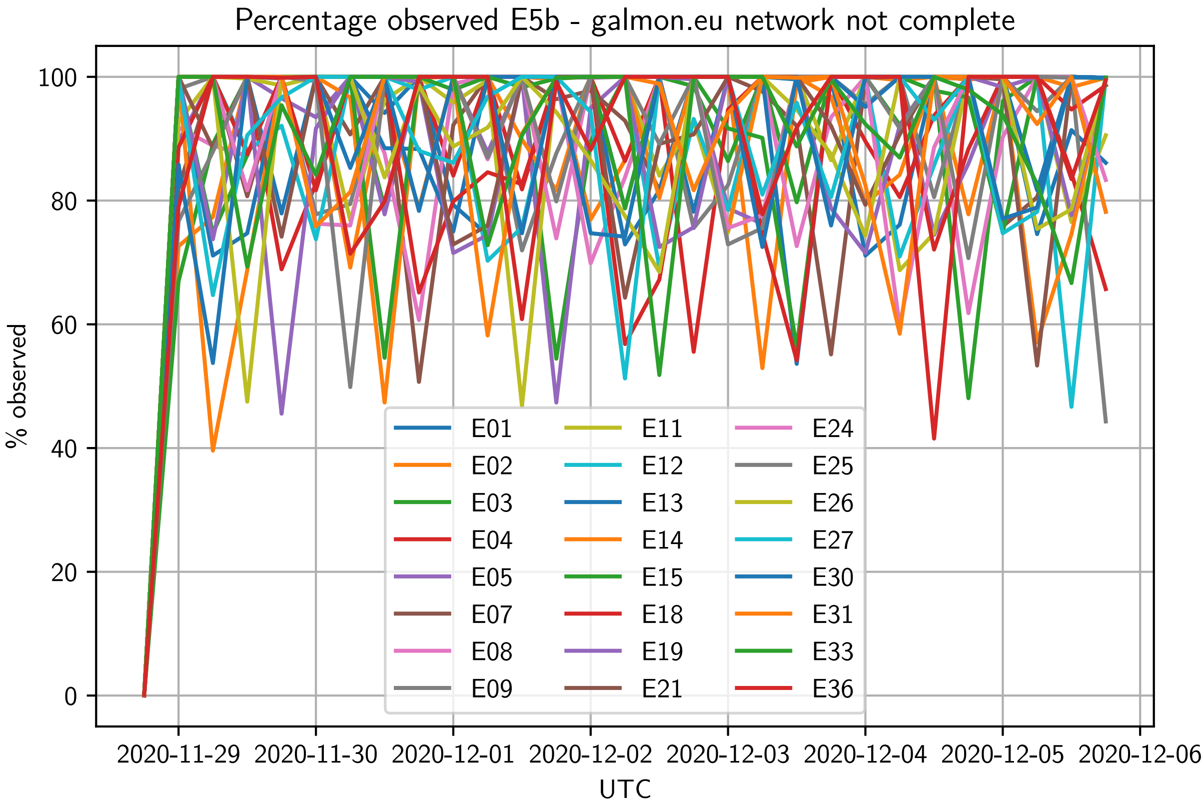
3.2 Percentage observed

The galmon.eu network strives for 100% coverage of all Galileo transmissions. This is not an easy bar to reach since many receivers will miss double percentage fractions of transmissions. We compensate for this by having a large number of receivers.

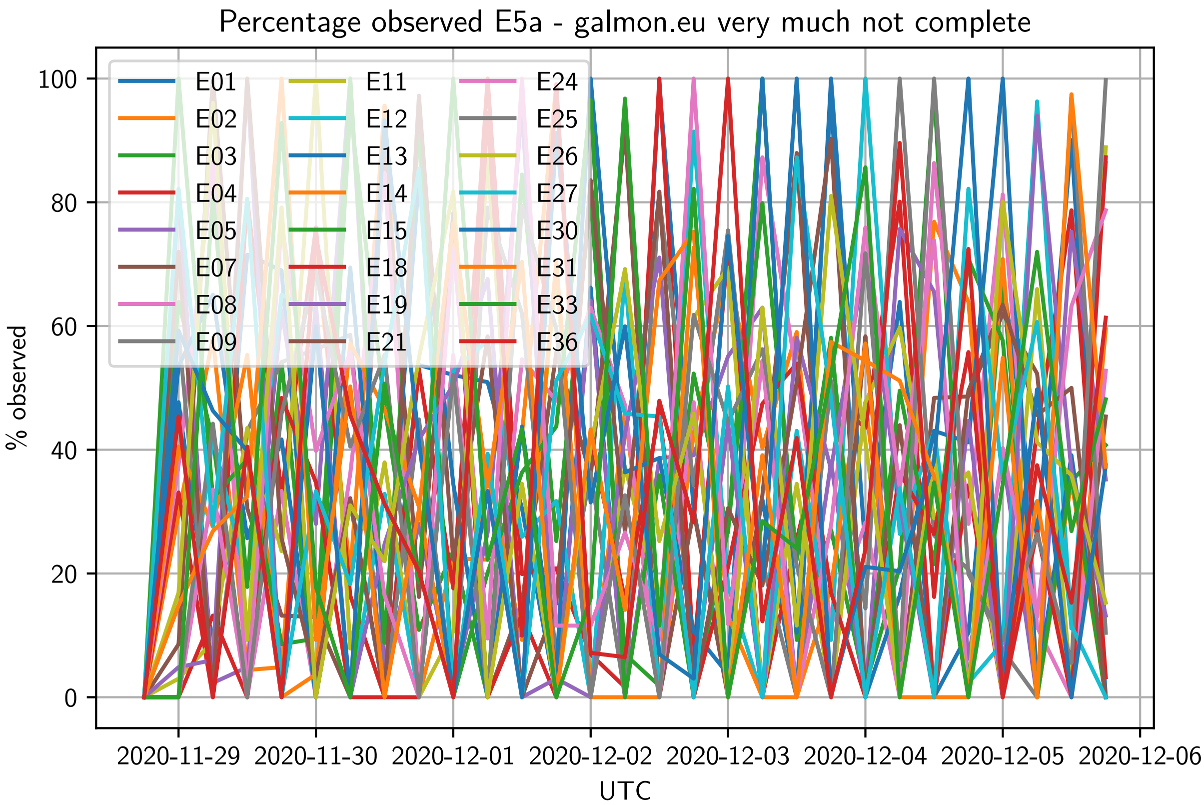
Despite this, some messages are not received. If some messages are missed briefly, this likely indicates a deficiency of the galmon.eu network. If there is a more prominent dip, this likely indicates a problem with the satellite. Note that it is normal for this graph to go to zero at the end or beginning of the reporting period.



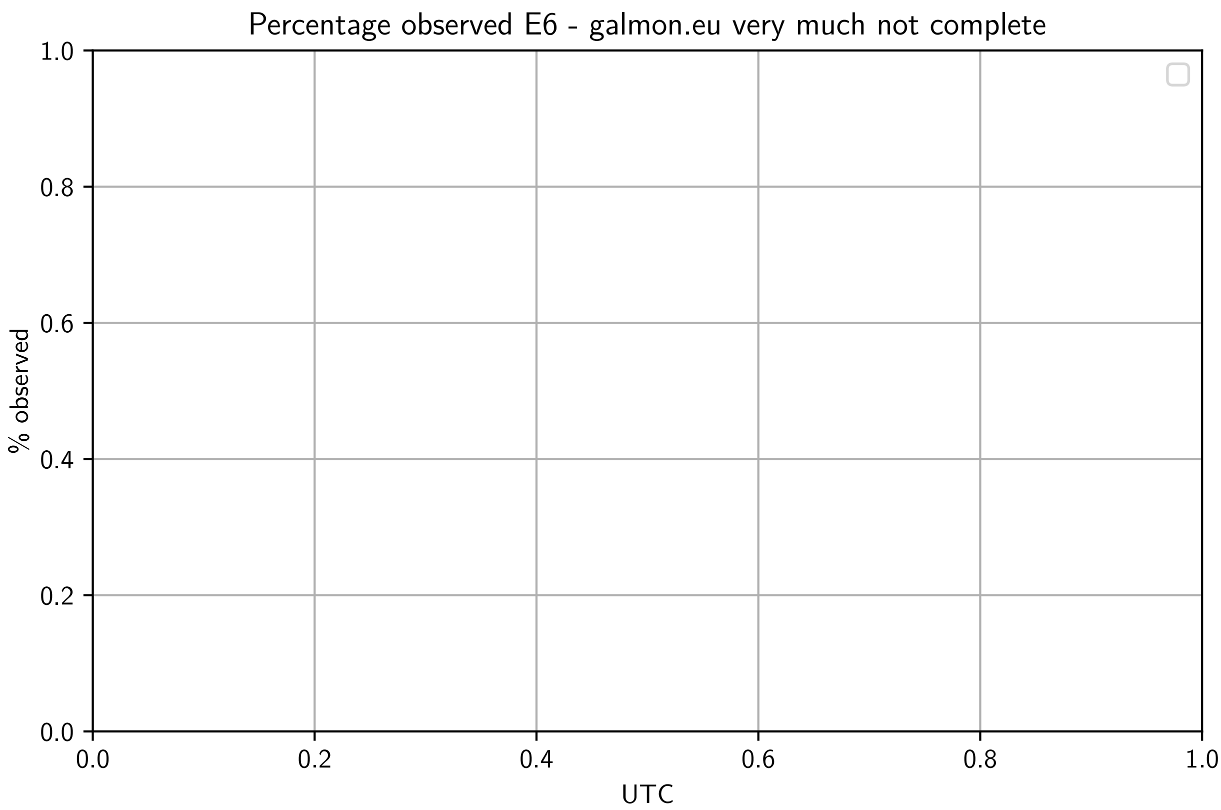
Our network also covers the E5b, E5a and even the E6 bands, but our coverage is far less complete:



Percentage observed E5b - galmon.eu network not complete
% observed
UTC
E01
E02
E03
E04
E05
E07
E08
E09
E11
E12
E13
E14
E15
E18
E19
E21
E24
E25
E26
E27
E30
E31
E33
E36



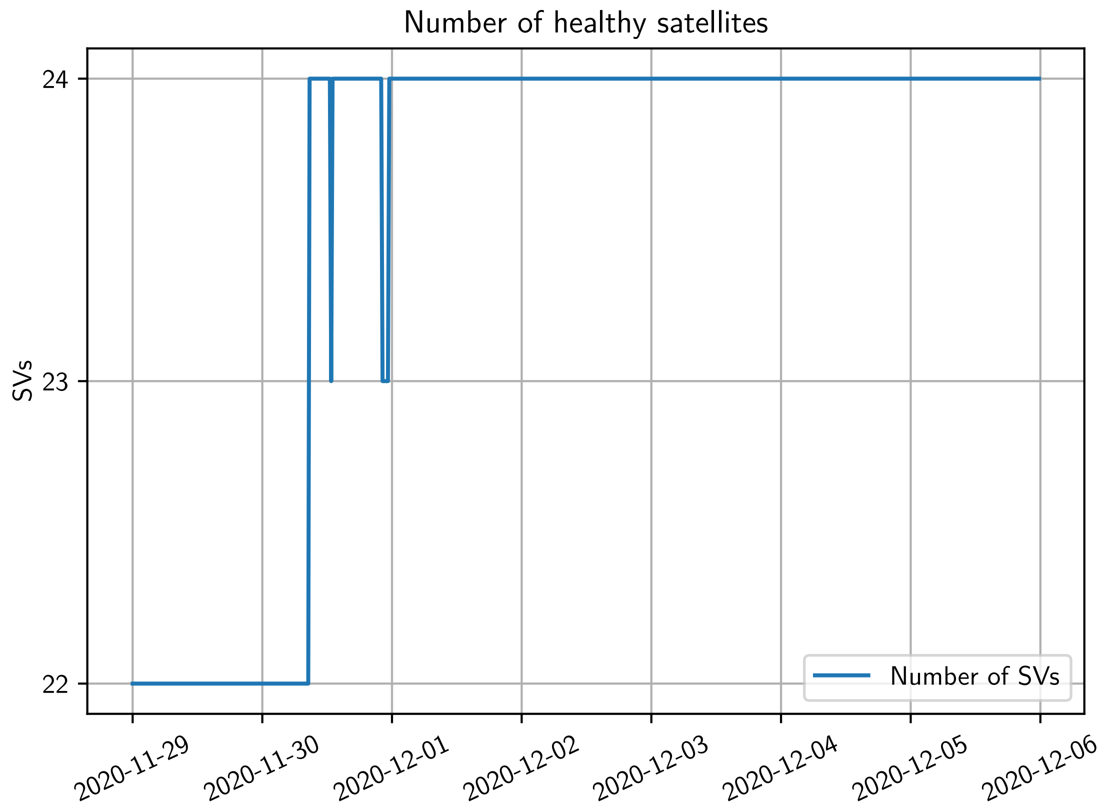
Percentage observed E5a - galmon.eu very much not complete
% observed
UTC
E01
E02
E03
E04
E05
E07
E08
E09
E11
E12
E13
E14
E15
E18
E19
E21
E24
E25
E26
E27
E30
E31
E33
E36



If you can spare us an SBF feed from your Septentrio device, this would be most helpful!

3.3 Healthy satellites

Satellites can be healthy, unhealthy or marginal. The difference between the last two categories is academic since no marginal satellites should be used.



In the following table, the distribution of status of all non-testing SVs can be observed:

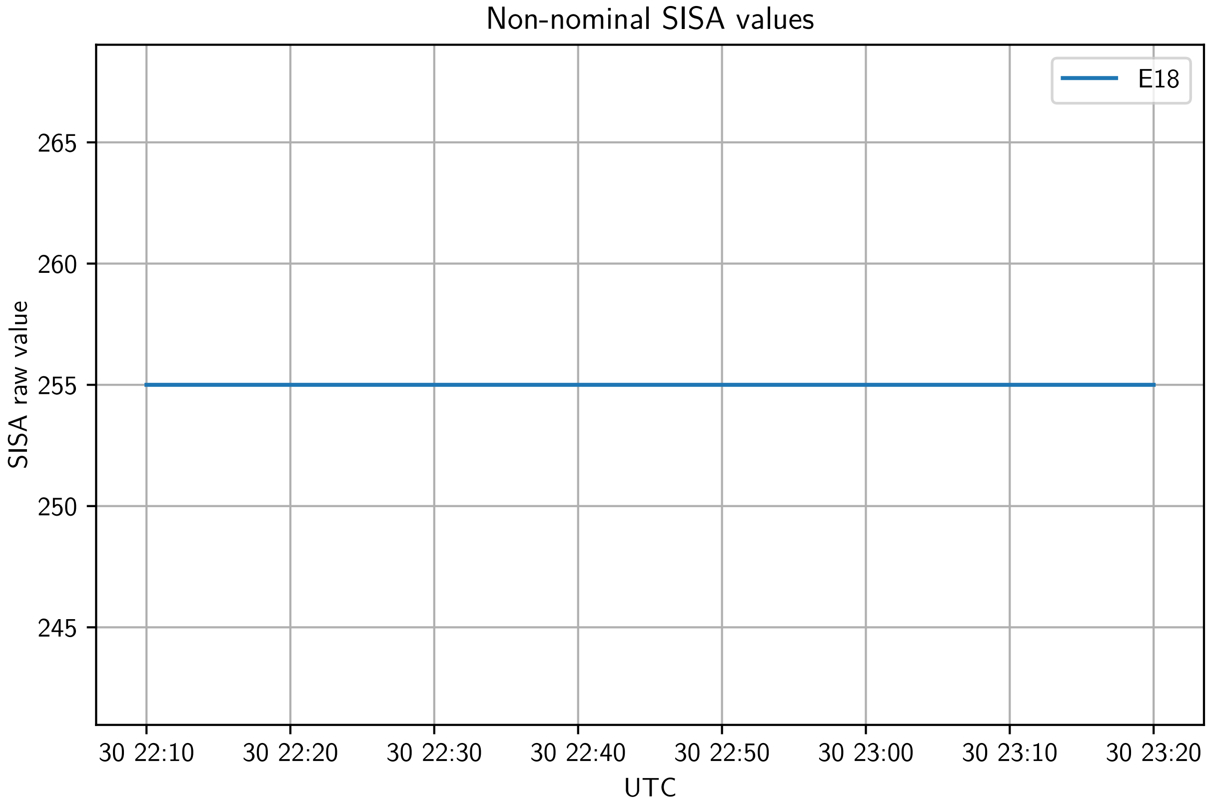
SV	unobserved	unhealthy	healthy	testing	napa	ripe	expired
E01	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E02	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E03	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E04	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E05	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E07	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E08	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E09	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E11	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E12	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E13	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E14	0.00%	0.10%	80.56%	19.35%	0.00%	0.00%	0.00%
E15	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E18	0.00%	0.00%	80.06%	19.35%	0.60%	0.00%	0.00%
E19	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E21	0.00%	0.00%	100.00%	0.00%	0.00%	0.20%	0.00%
E24	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E25	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E26	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E27	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E30	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E31	0.00%	0.00%	100.00%	0.00%	0.00%	0.20%	0.00%
E33	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
E36	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
Tot	0.00%	0.00%	98.36%	1.61%	0.02%	0.02%	0.00%

Table 3.1: Satellite status table for E1/E5b I/NAV

This table defines a "ripe" ephemeris as one older than 100 minutes, and an expired one as older than 4 hours (in accordance with the Galileo Service Definition document).

3.4 Signal In Space Accuracy (SISA) and NAPA

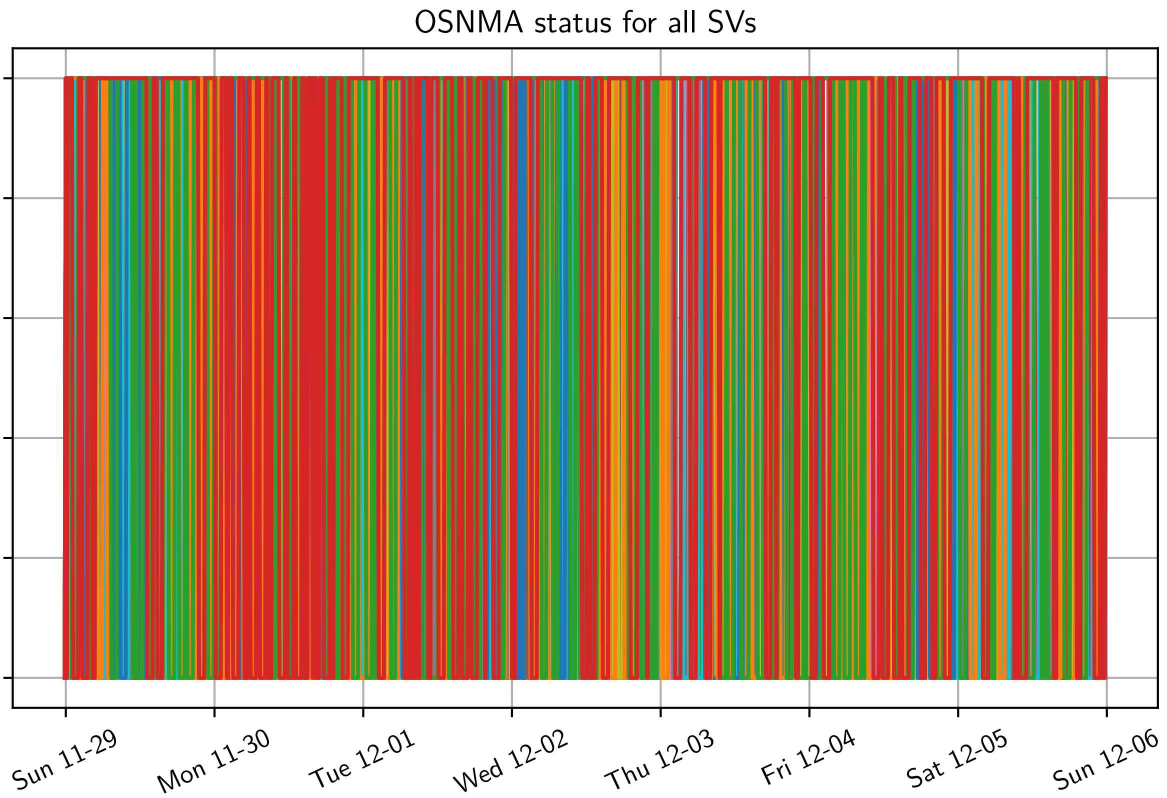
The nominal Signal In Space Accuracy value for Galileo is currently 312 centimeters. This graph shows occasions where Galileo satellites broadcast a different SISA value. If everything is operating as planned, this graph is empty.



Chapter 4

OSNMA

Open Service Network Message Authentication (OSNMA) is a new protocol to add digital signatures to Galileo navigation messages. OSNMA is currently in testing, but we're already keeping track of it. To learn more about OSMA, please turn to this series of posts that attempt to explain this clever and novel protocol.

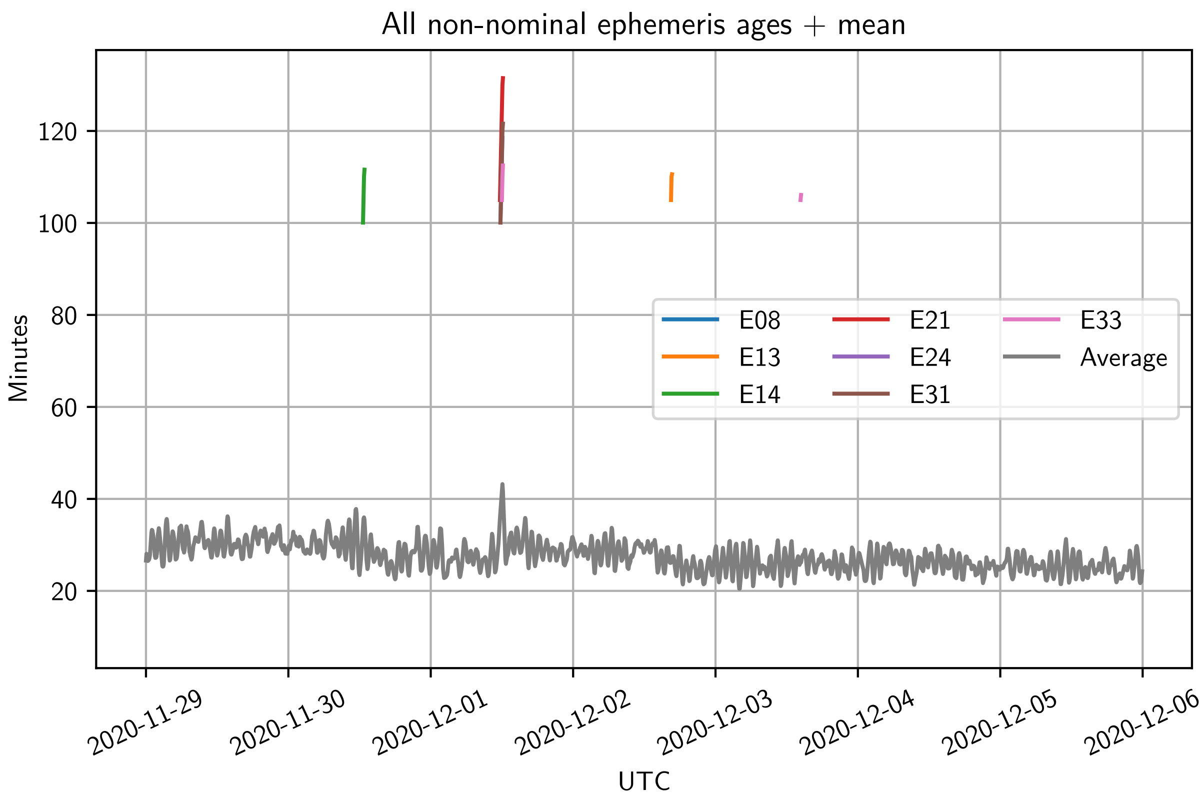


Chapter 5

Ephemerides and ground segment capacity

5.1 Ephemeris age

This graph shows the average ephemeris age, defined as time passed since t_{0e}. In addition, any non-nominal ephemerides ages, defined as more than 100 minutes old, will also be shown.



Note that this graph reports the time from t_{0e} for an ephemeris. A "second batch" ephemeris, which is transmitted by Galileo satellites that haven't received an update in three hours, will look "fresh" on this graph. The next section plots which ephemerides were actually second or later batches.

5.2 Ground station capacity and non-prime batches

The Galileo Ground Segment has five uplink stations: Papeete, Kourou, Svalbard, Réunion and Noumea. Nominally, each of these station has four dishes to uplink data to the Galileo satellites. In practice, this nominal capacity is not available.

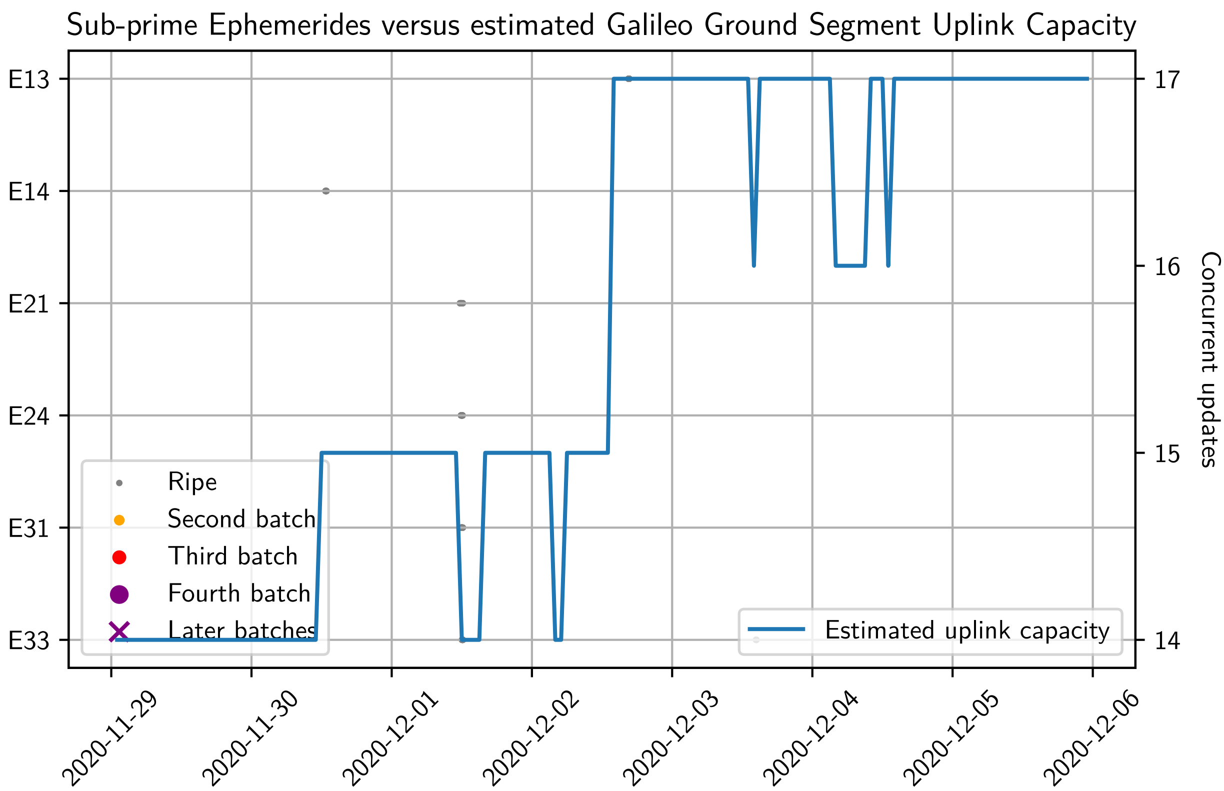
Galileo satellites are nominally updated at least once an hour, and during normal operations, no ephemerides older than 100 minutes are observed.

Frequently however, the uplink capacity is not enough to maintain this update cadence. Usually, 14 dishes are active, and this suffices. If one of these dishes fails for too long, or if multiple dishes are not operational, Galileo satellites continue providing service based on pre-uploaded 'batches' of data.

The second batch is fielded after 3 hours, and the third one after 6 hours. There are 8 batches on board, which provide for 24 hours of autonomous service.

It should be noted however that these later batches contain no new information. If an on-board clock has an anomaly, the pre-uploaded data doesn't know about this, and this can lead to problems and reduced accuracy.

The following graph shows the estimated number of operational dishes, plus for each Galileo satellite if it was serving second, third, fourth or later batch information. In addition, first-batch ephemerides older than 100 minutes get shown as 'ripe'.



In a nominal week, this graph shows a straight blue line denoting 14 active dishes.

The number of operational dishes can only be estimated. The galmon.eu network observes how many Galileo satellites receive updates in unison. The maximum number of simultaneous updates over an hour is taken as an estimate of the number of dishes operational during that hour.

Chapter 6

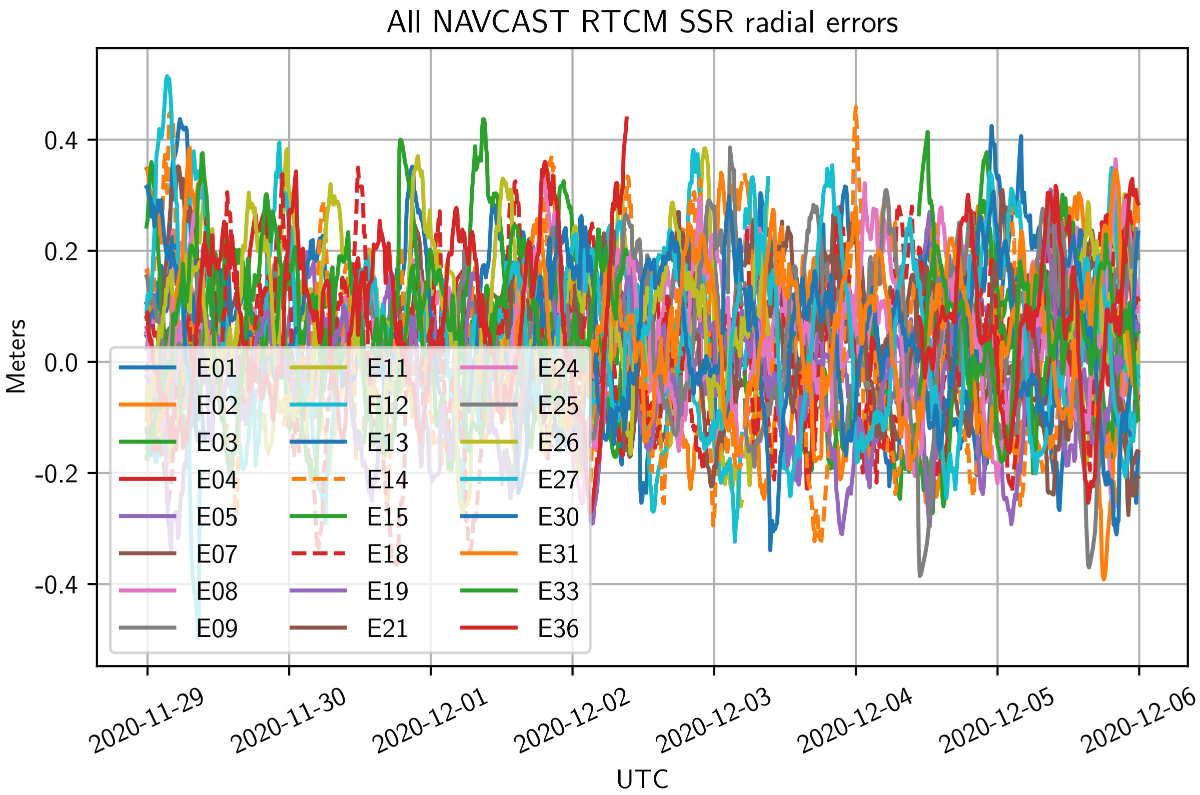
Accuracy

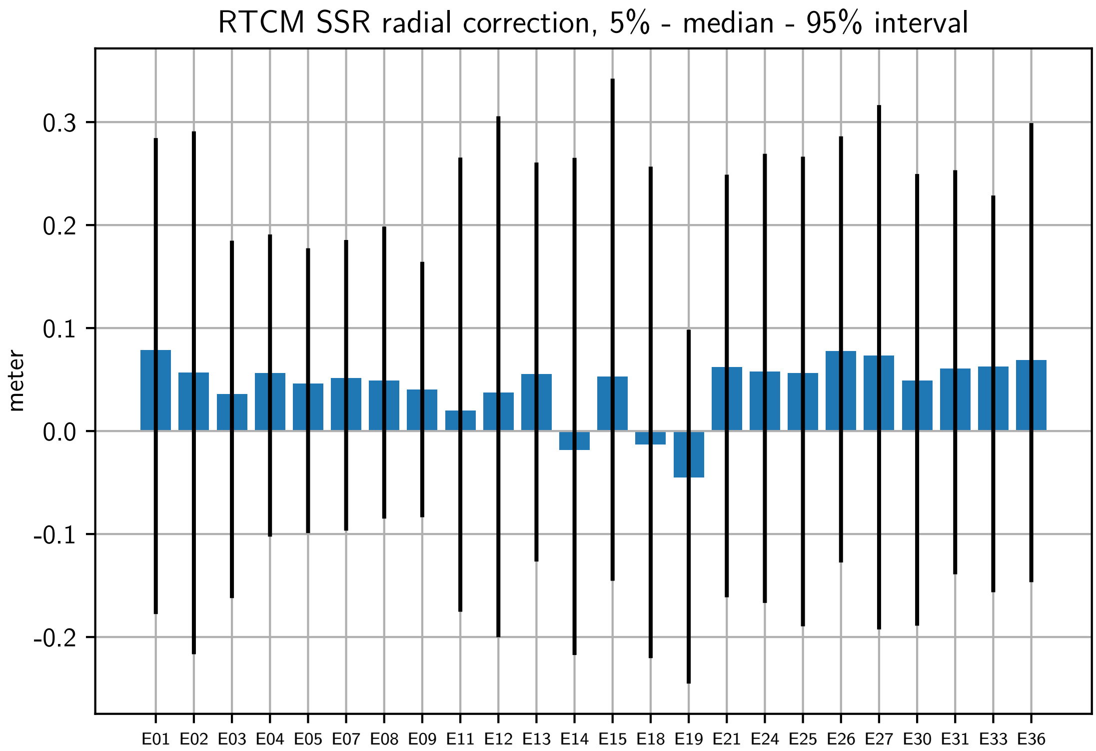
6.1 Radial error

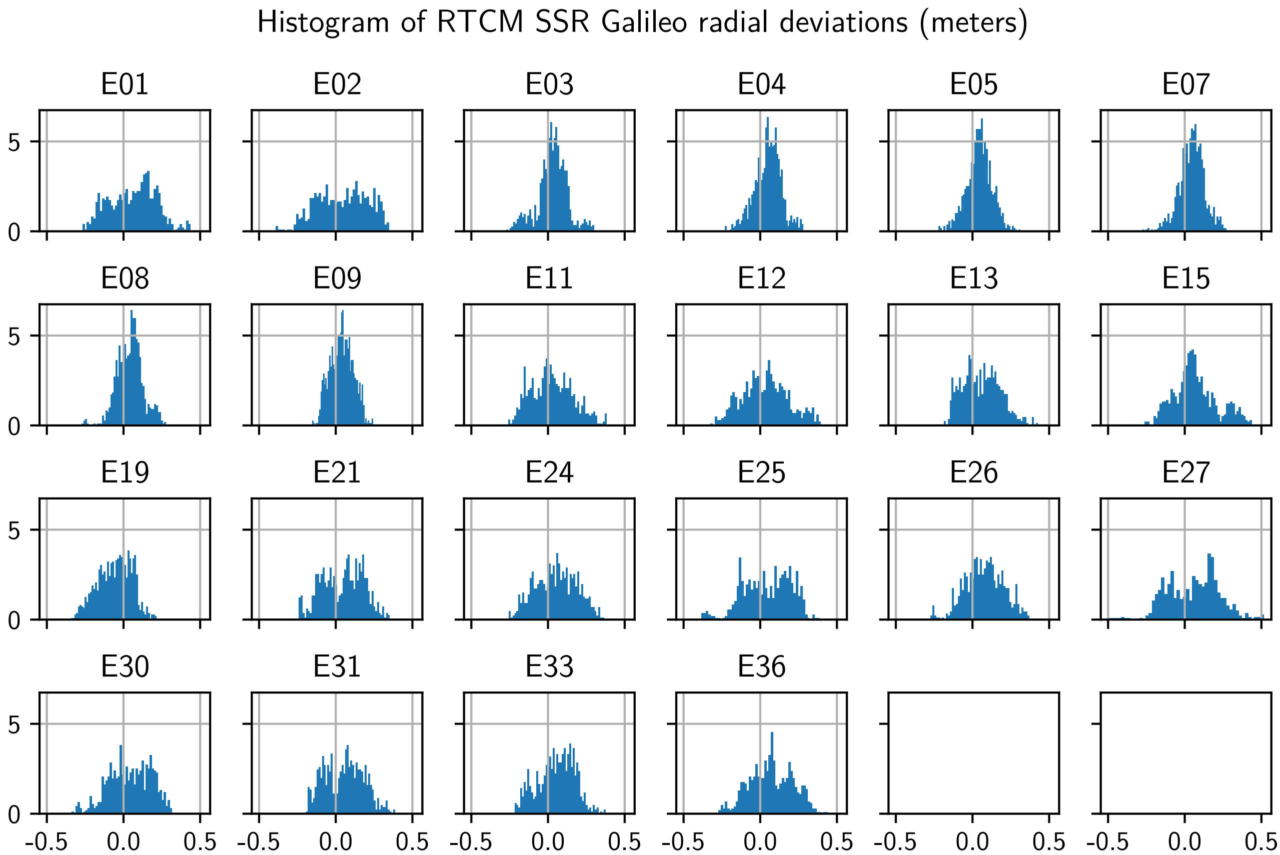
In a nominal situation, this graph shows many overlapping lines all clustered around 0 meters error. If any SV deviates significantly, this shows up in subsequent graphs.

Details for individual satellites can be found at the end of this report.

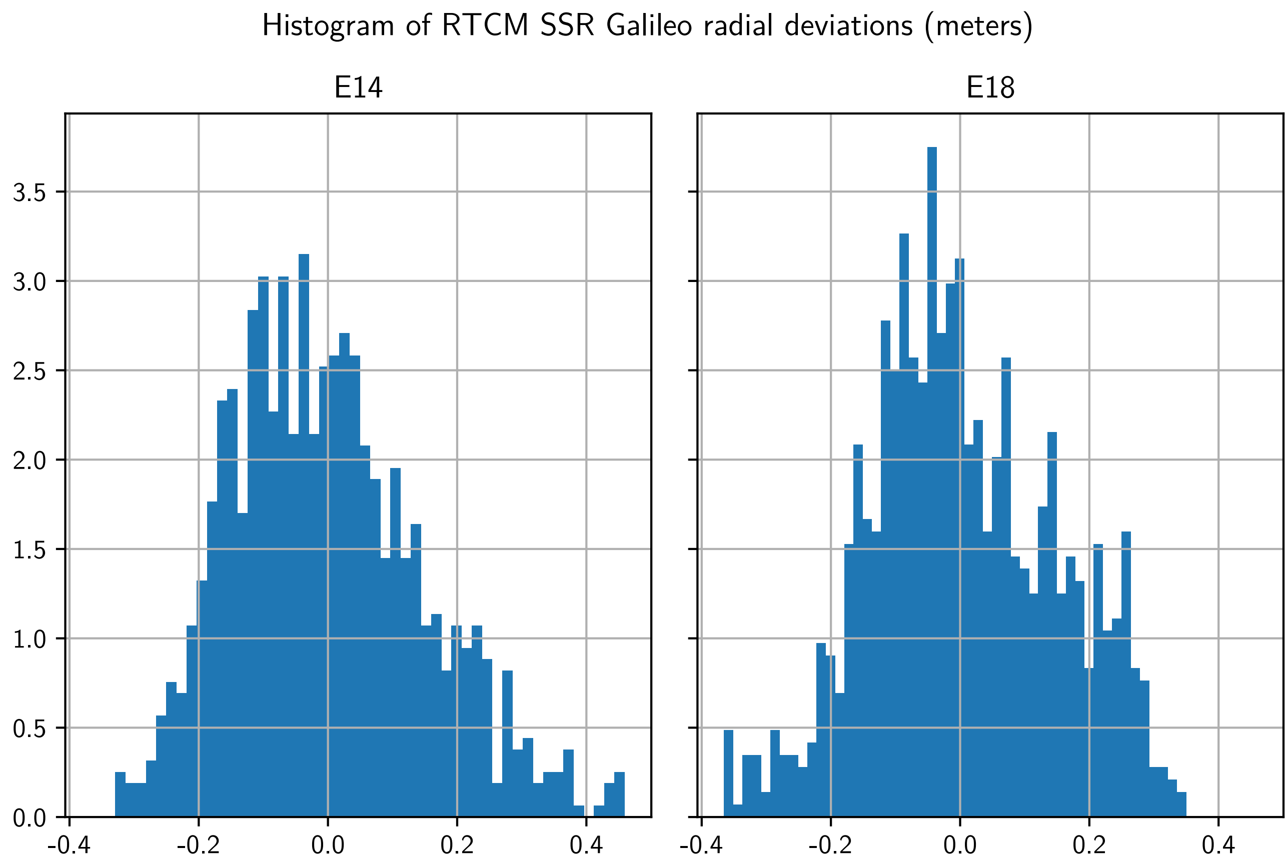
Note that the RTCM radial data appears to have a 5 centimeter bias. This may reflect a transposition to a different coordinate system.







Separately, a plot for the auxiliary satellites E14 and E18, which often have far larger excursions:



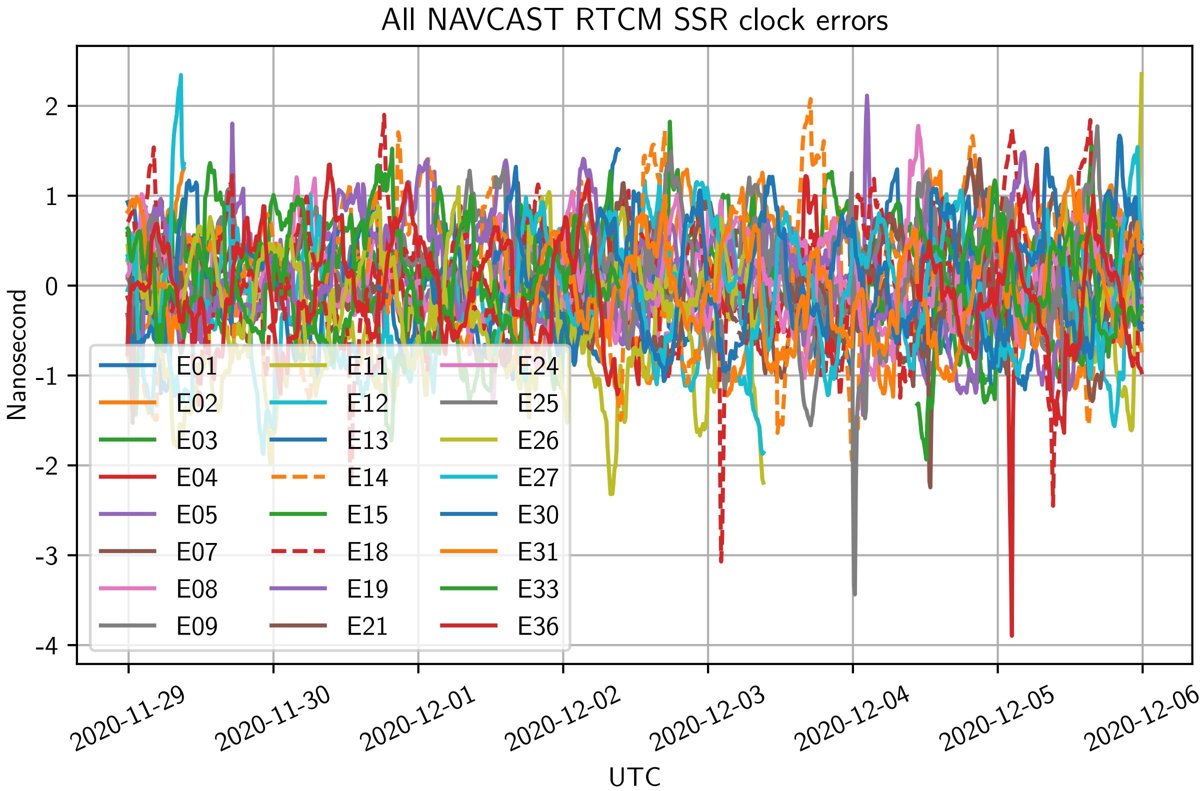
(note the likely different scale on the x-axis)

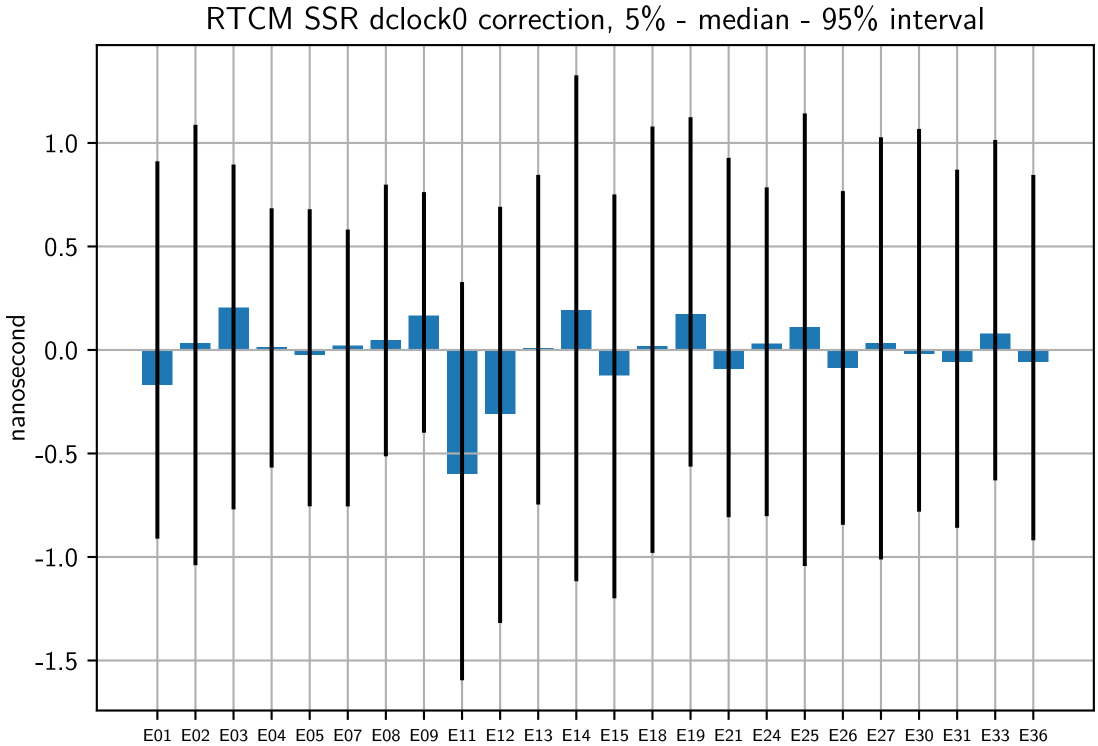
6.2 Clock error

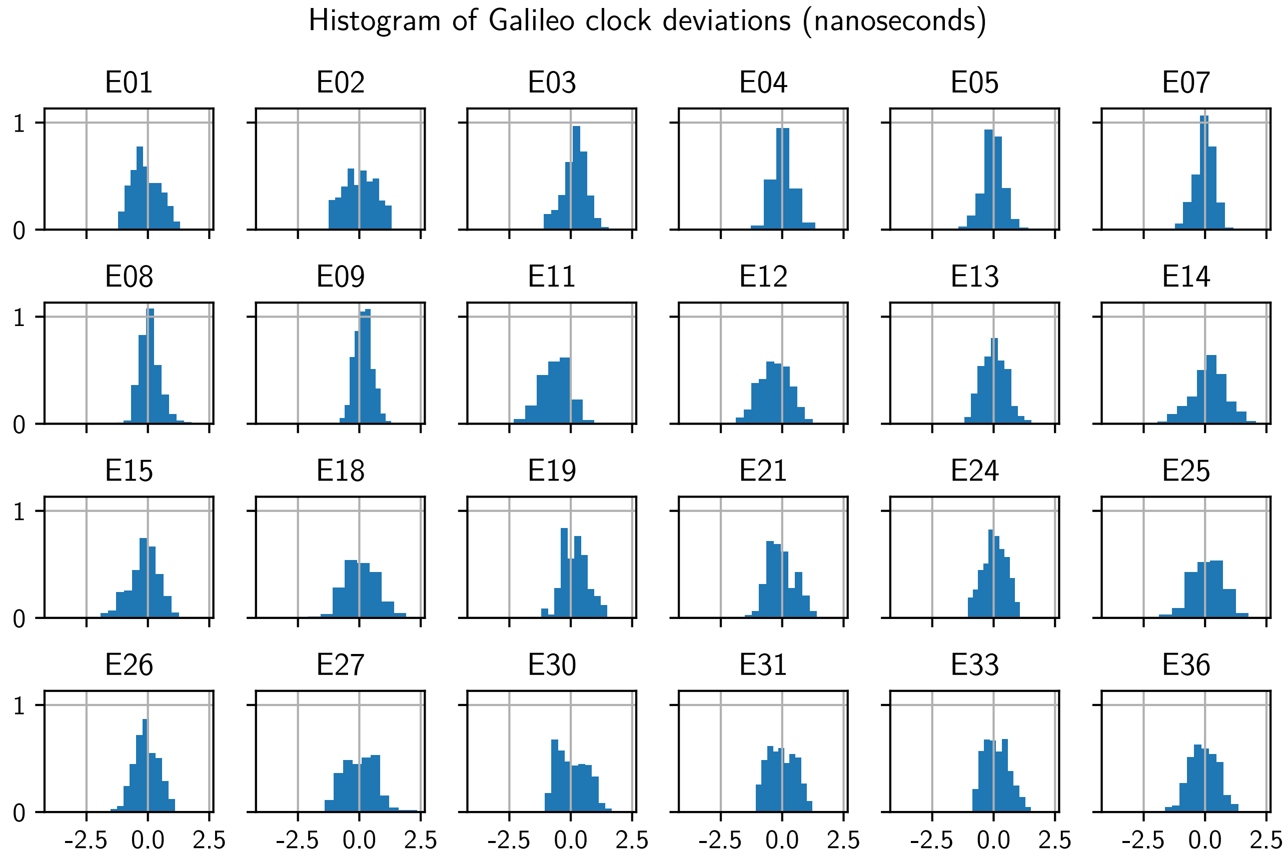
In a nominal situation, this graph shows many overlapping lines all clustered around 0 nanosecond error. If any SV deviates significantly, this shows up in subsequent graphs.

Details for individual satellites can be found at the end of this report.

Note that the RTCM clock error data as provided by DLR/NAVCAST and CNES is expressed in terms of a metric which corrects the F/NAV clock to the I/NAV clock. This creates non-physical corrections. To compensate, the data as presented in this report undoes the I/NAV-F/NAV transition. Further details on this situation can be found in two blogposts by independent researcher Daniel Estévez, "About Galileo BGDs" and "RTCM clock corrections for Galileo E24".


All NAVCAST RTCM SSR clock errors
Nanosecond
UTC
2
1
0
-1
-2
-3
-4
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
E01
E02
E03
E04
E05
E07
E08
E09
E11
E12
E13
E14
E15
E18
E19
E21
E24
E25
E26
E27
E30
E31
E33
E36


RTCM SSR dclock0 correction, 5% - median - 95% interval
nanosecond
1.0
0.5
0.0
-0.5
-1.0
-1.5
E01 E02 E03 E04 E05 E07 E08 E09 E11 E12 E13 E14 E15 E18 E19 E21 E24 E25 E26 E27 E30 E31 E33 E36

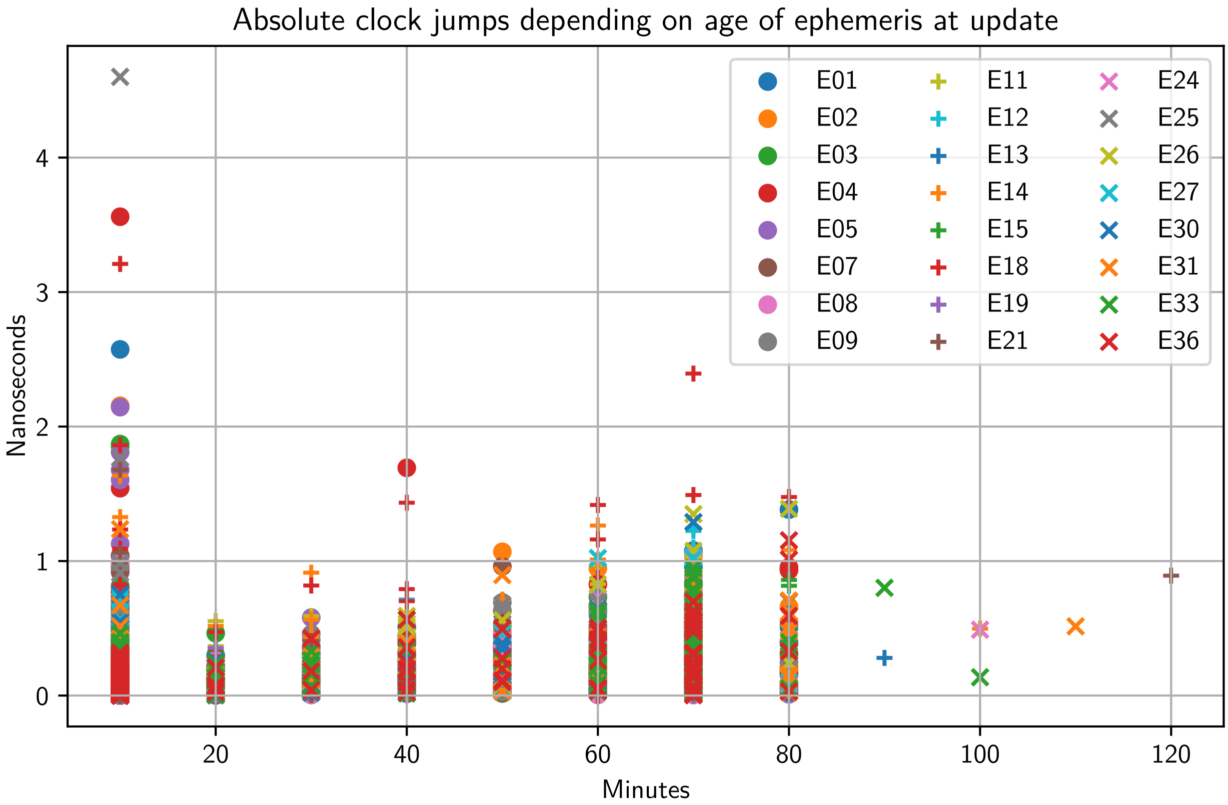


6.3 Clock stability

The Galileo clocks are monitored from the ground to determine their offset from Galileo System Time (GST), as well as their drift rate. Periodically, mostly every ten minutes, new parameters are uplinked. Occasionally however updates may appear only after 90 minutes. This is all nominal behaviour.

However, such delayed updates can lead to larger shifts in clock corrections, which are indicative of clock behaviour not being modeled well (enough).

The scatterplot below shows update latency versus absolute clock jumps for all Galileo satellites.


Absolute clock jumps depending on age of ephemeris at update
Nanoseconds
Minutes
0
1
2
3
4
20
40
60
80
100
120
E01
E02
E03
E04
E05
E07
E08
E09
E11
E12
E13
E14
E15
E18
E19
E21
E24
E25
E26
E27
E30
E31
E33
E36

Chapter 7

Global performance

The performance for average and worst user locations features large in the Galileo Service Definition Document. Of specific note is availability (coverage, visibility of 4 or more satellites) with an elevation more than 5 degrees above the horizon.

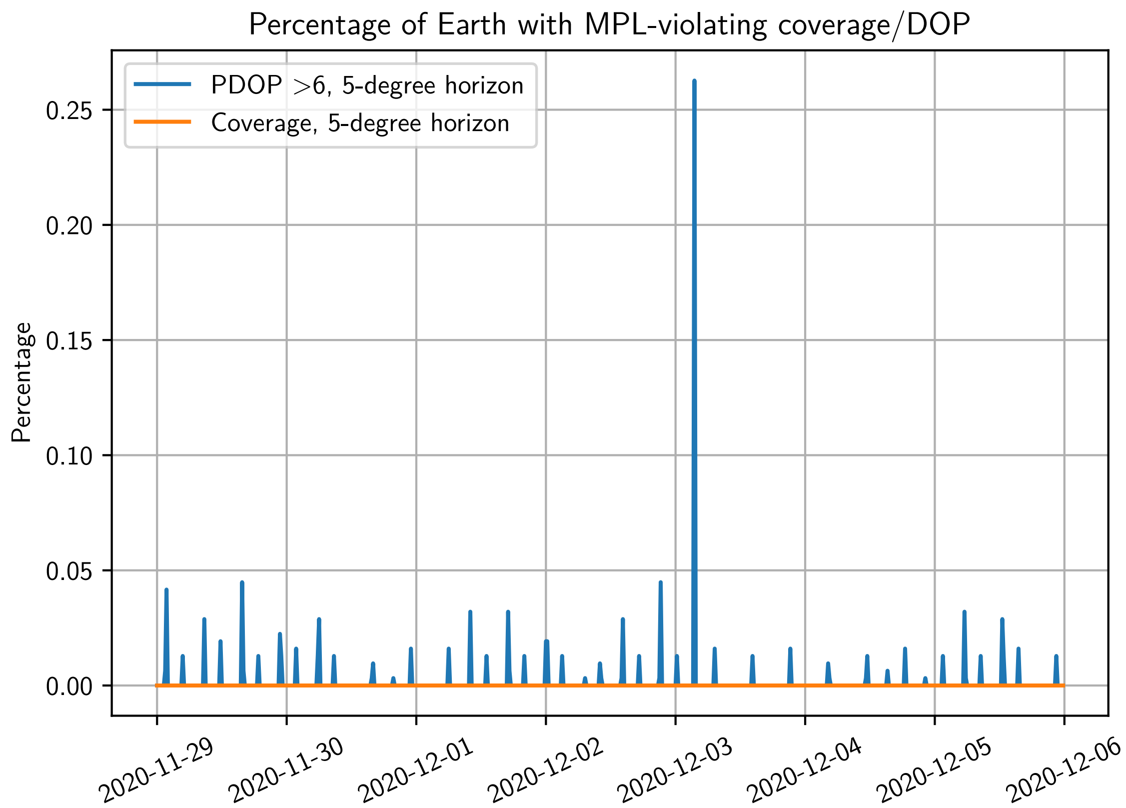
In addition, we plot the perhaps more meaningful similar measure with a view of more than 10 degrees above the horizon.

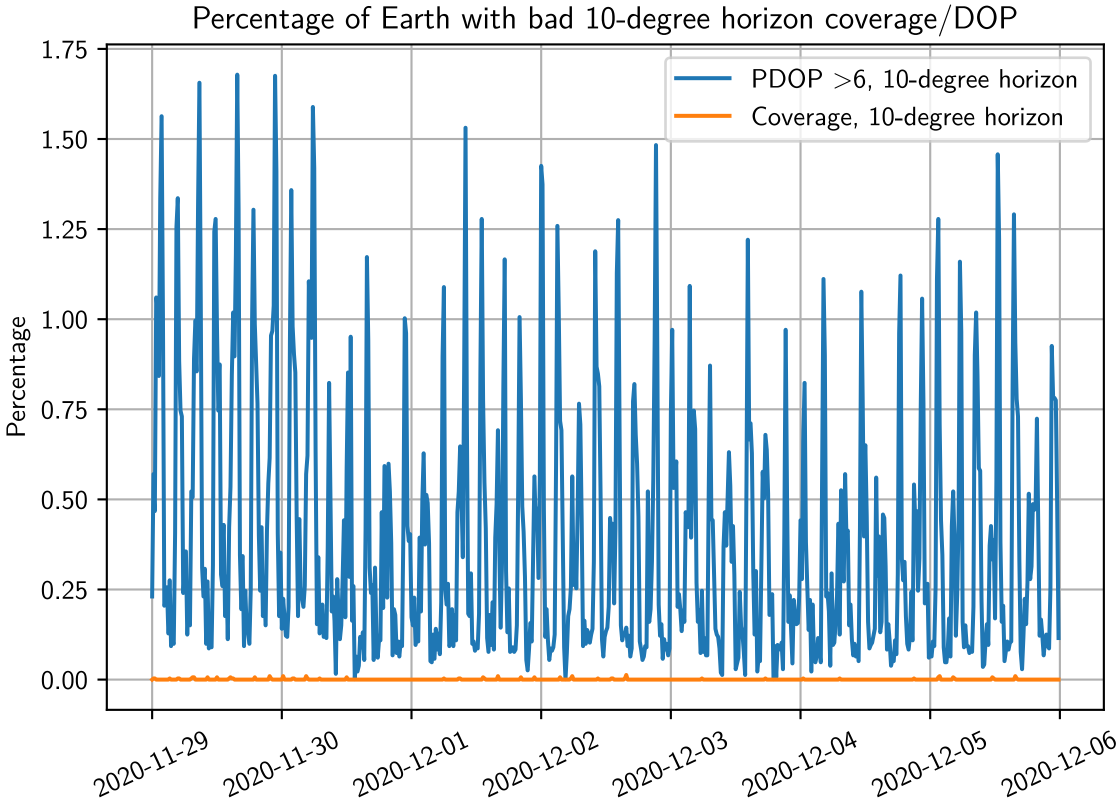
Note that these graphs show minute variations, where sometimes only tiny fractions of the Earth's surface are impacted.

7.1 PDOP and coverage

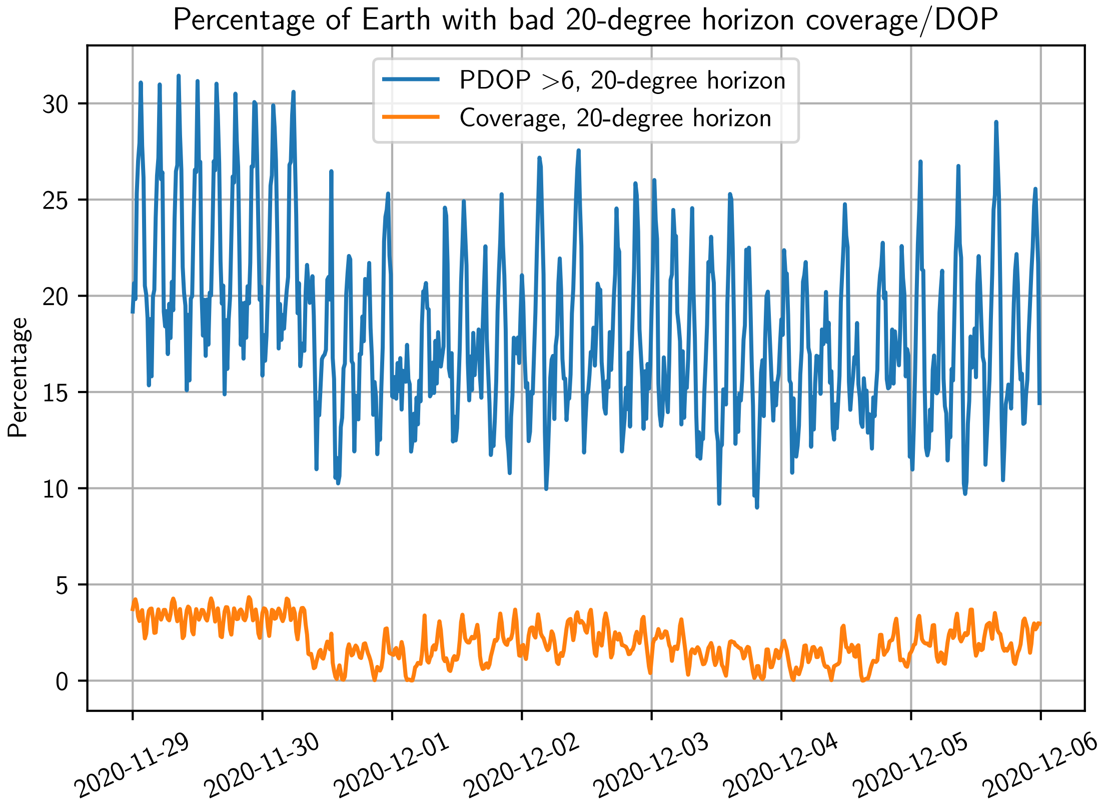
This week, on average 0.0% of the earth's surface violated the PDOP performance level for 5 degree elevation satellites, while 0.4% was violated for 10 degree elevation.

In addition, 0.0% did not see at least 4 satellites more than 5 degrees above the horizon, while 0.0% did not do so for more than 10 degrees above the horizon.





Note that a 20 degree horizon is not part of any minimum performance level definition, it does correspond to what users experience in cities:

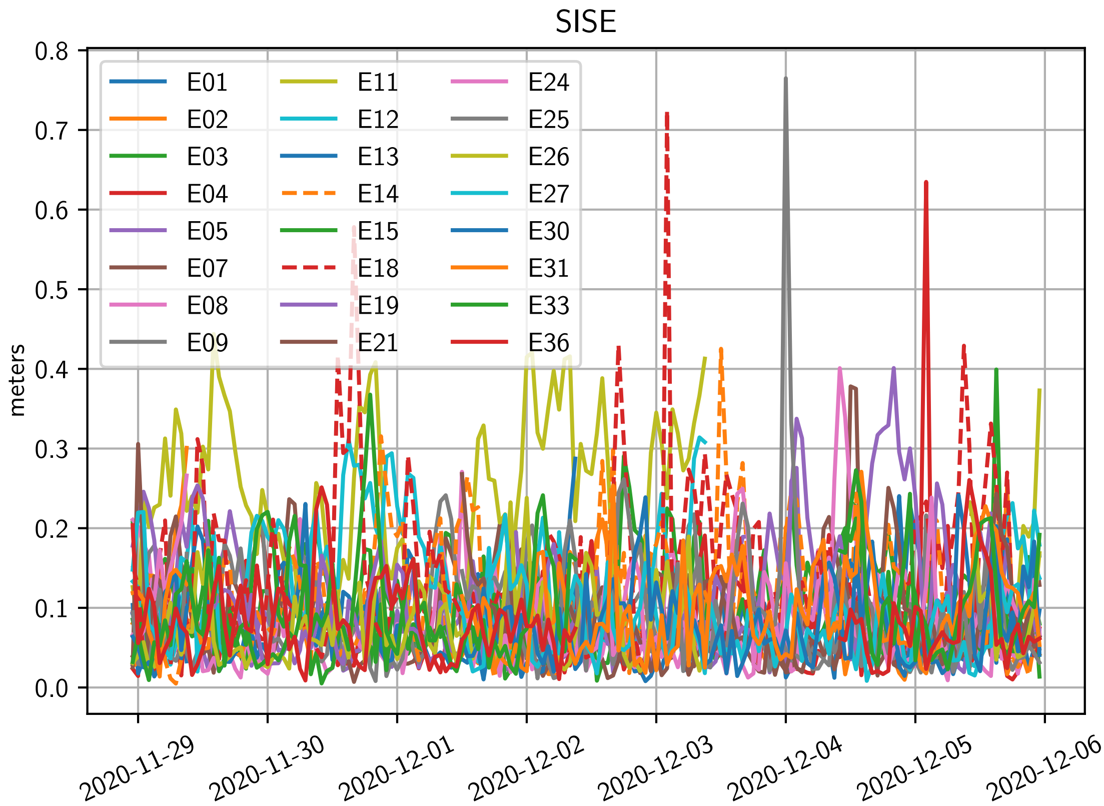


7.2 Signal In Space Error (SISE)

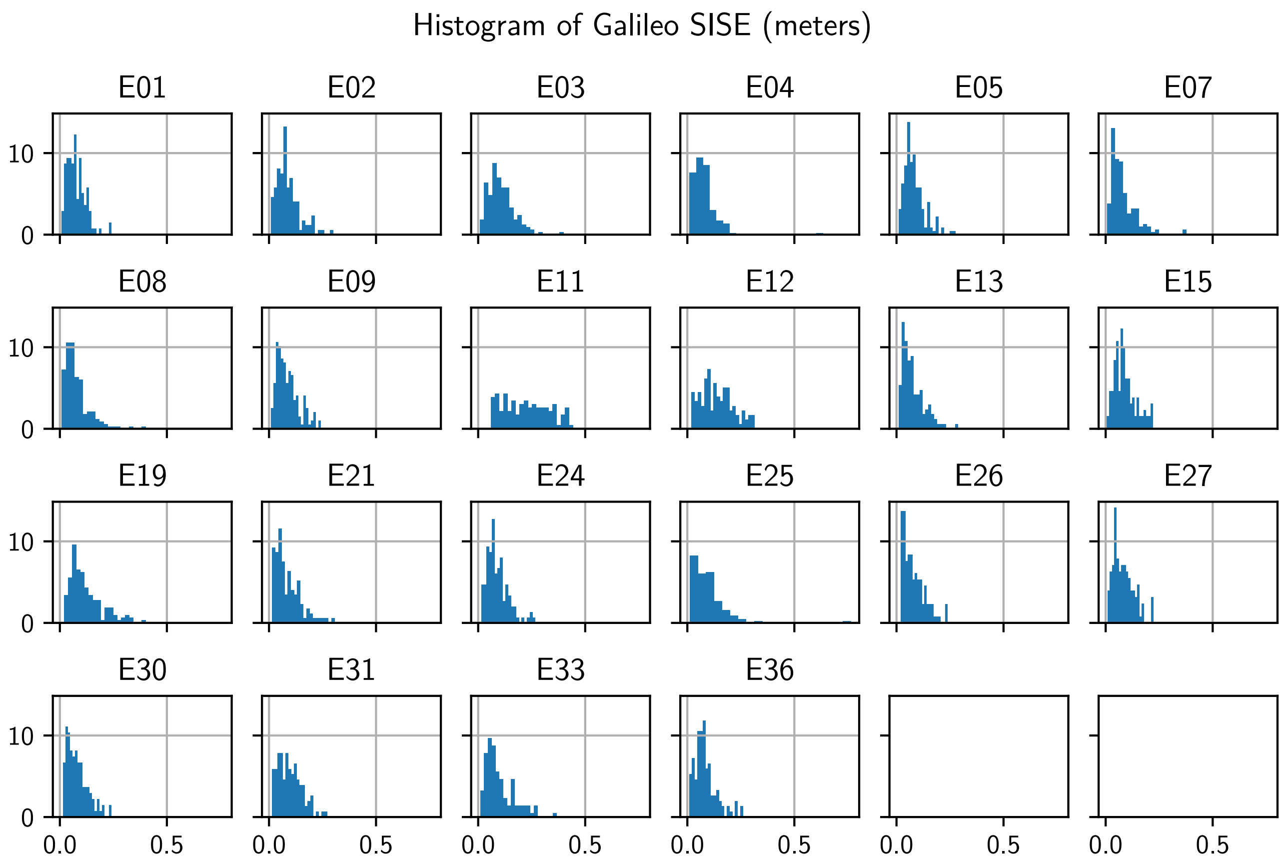
The data in this section is based on the approximation formula from section C.4.3.2 from the Galileo Service Definition Document.

The source of the corrections is the realtime NAVCAST data from Spaceopal/DLR. This data has, as usual, been adjusted for the F/NAV-I/NAV clock situation. In addition, an observed bias of around 5 centimeters has been deducted from the radial error.

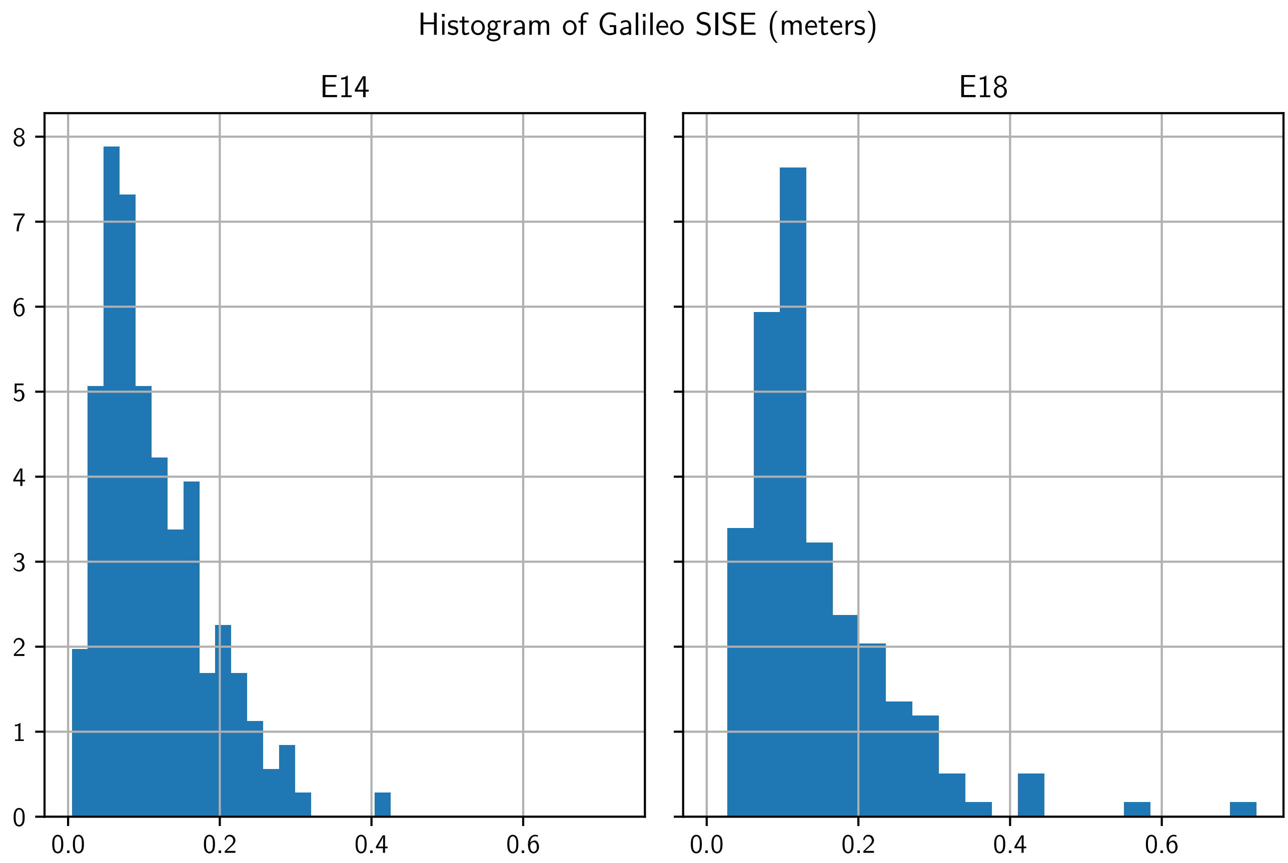
The first graph shows all SISE values for all SVs, and should show a lot of data quite close to 0 meters (usually 10 centimeters).



This second graph shows a histogram of Signal In Space Errors for all Galileo SVs:



And finally a dedicated graph for the two auxiliary satellites E14 and E18, which often have larger excursions. Note the possily different x-axis scale:

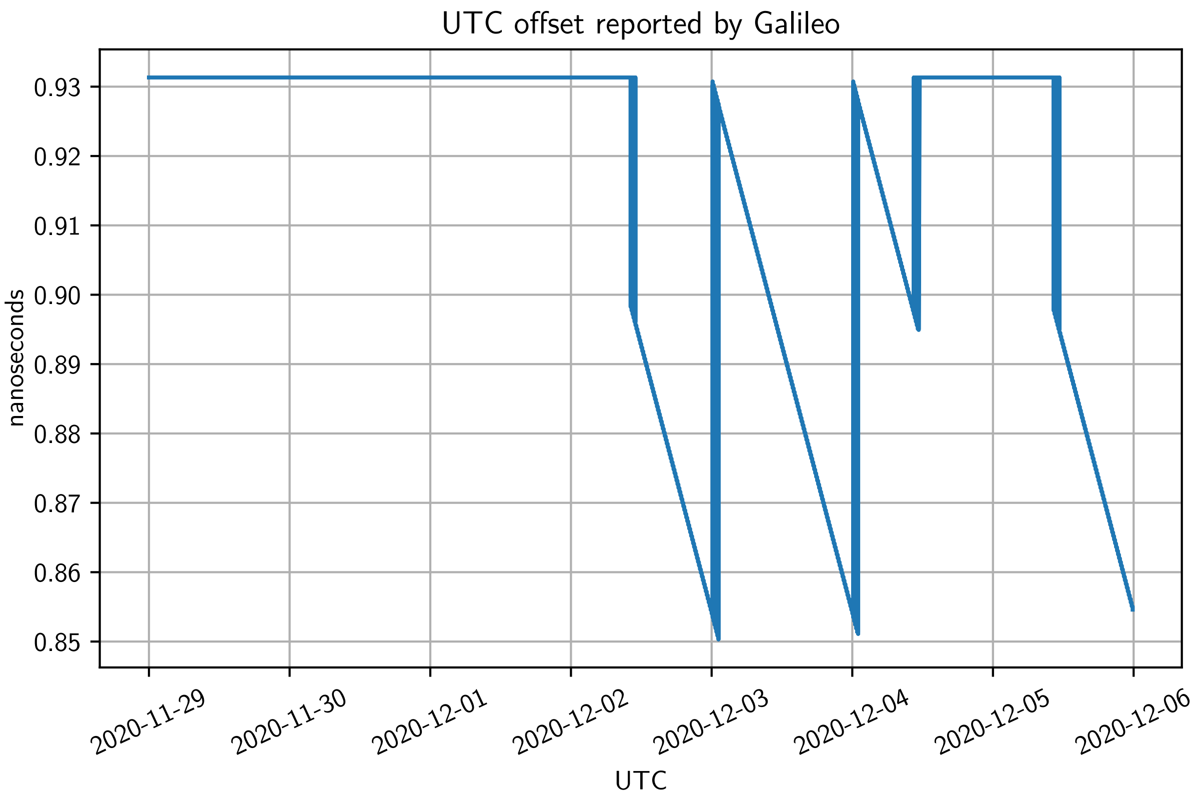


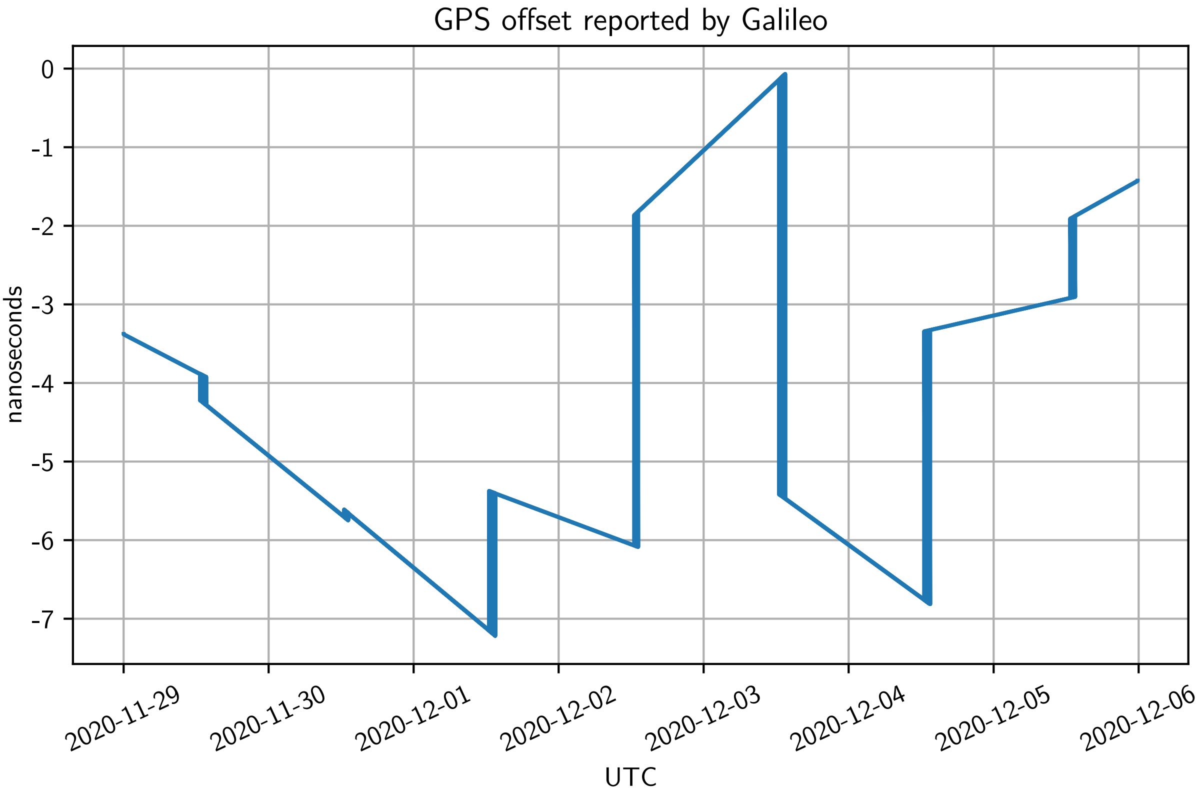
Chapter 8

UTC offset, GPS offset (GGTO)

8.1 Broadcast offset parameters

Galileo satellites broadcast their offset between "Galileo Time" (GST), UTC and GPS Time. These graphs show what offsets are transmitted.



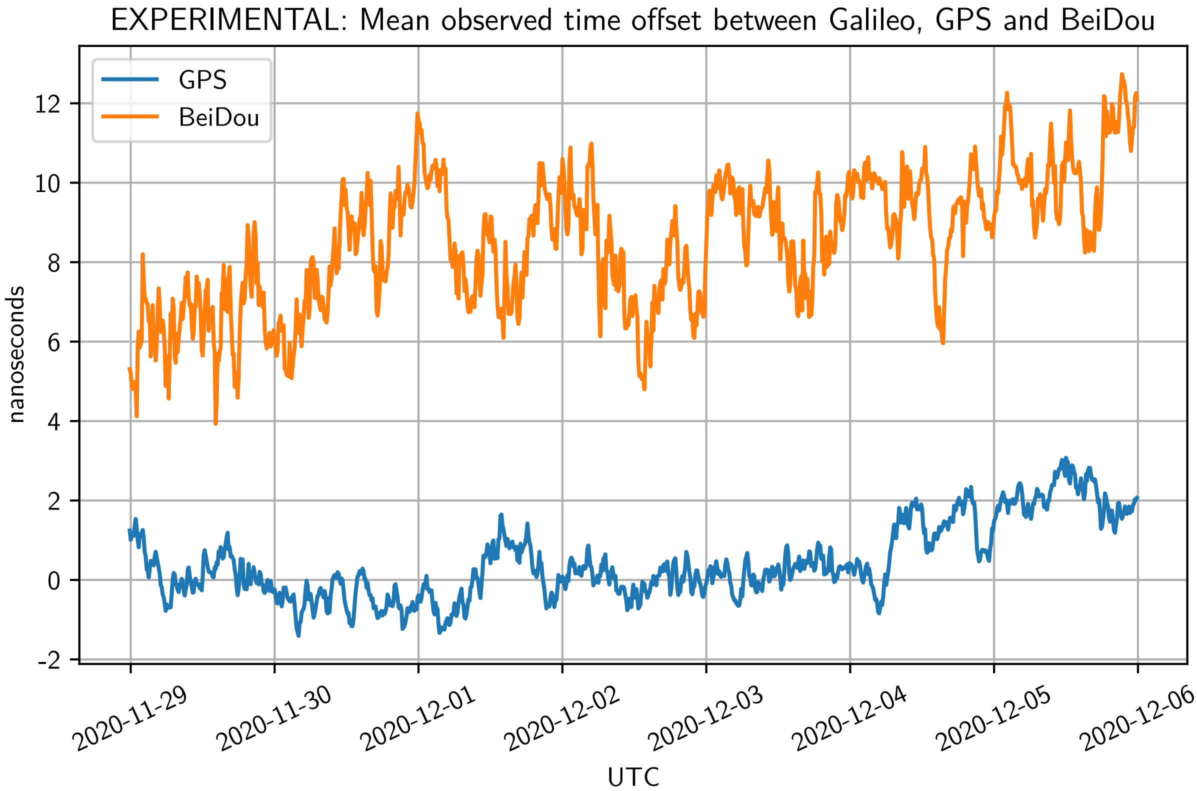


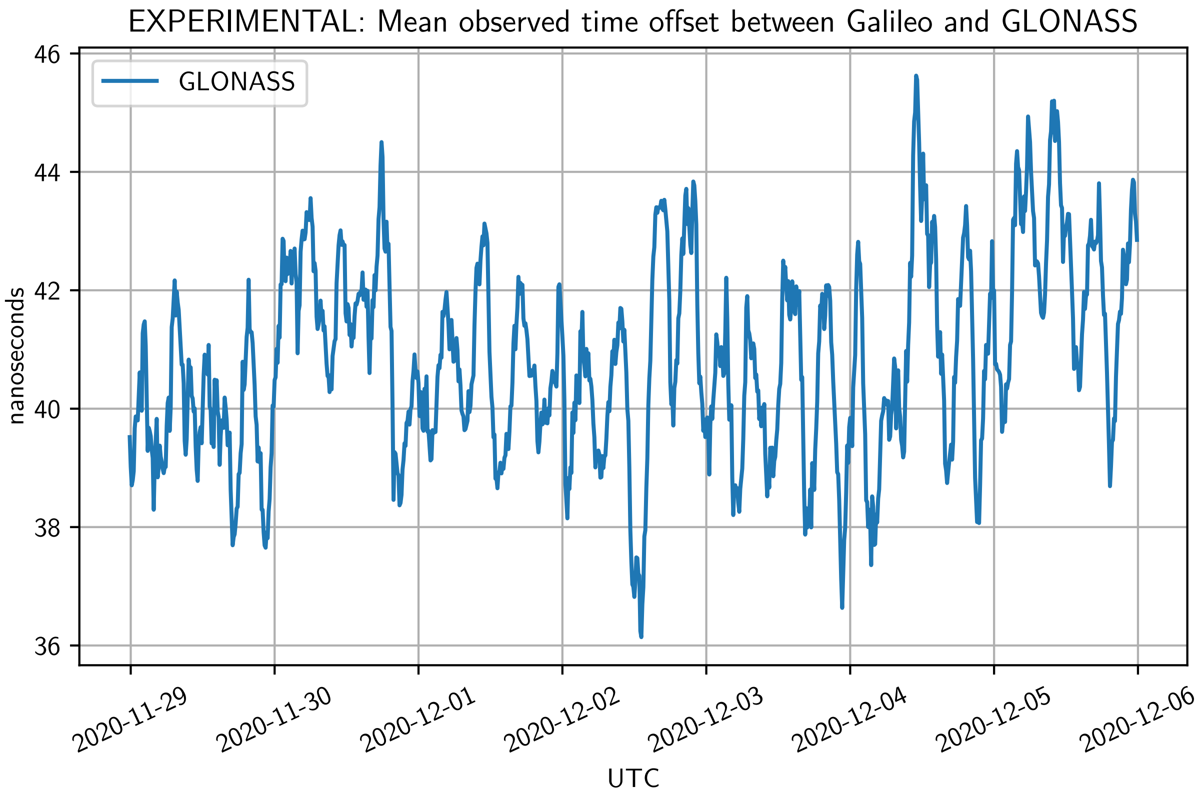
8.2 Measured time offsets between constellations

Since early July, the Galmon.eu networks attempts to measure the offset between the system times of Galileo, GPS, BeiDou and GLONASS.

Our individual receivers report offsets that appear to be distributed normally around the "actual" offset.

From UTC midnight of the 10th of July and onwards, sufficient receivers are participating that the offsets average out to something that might be real.

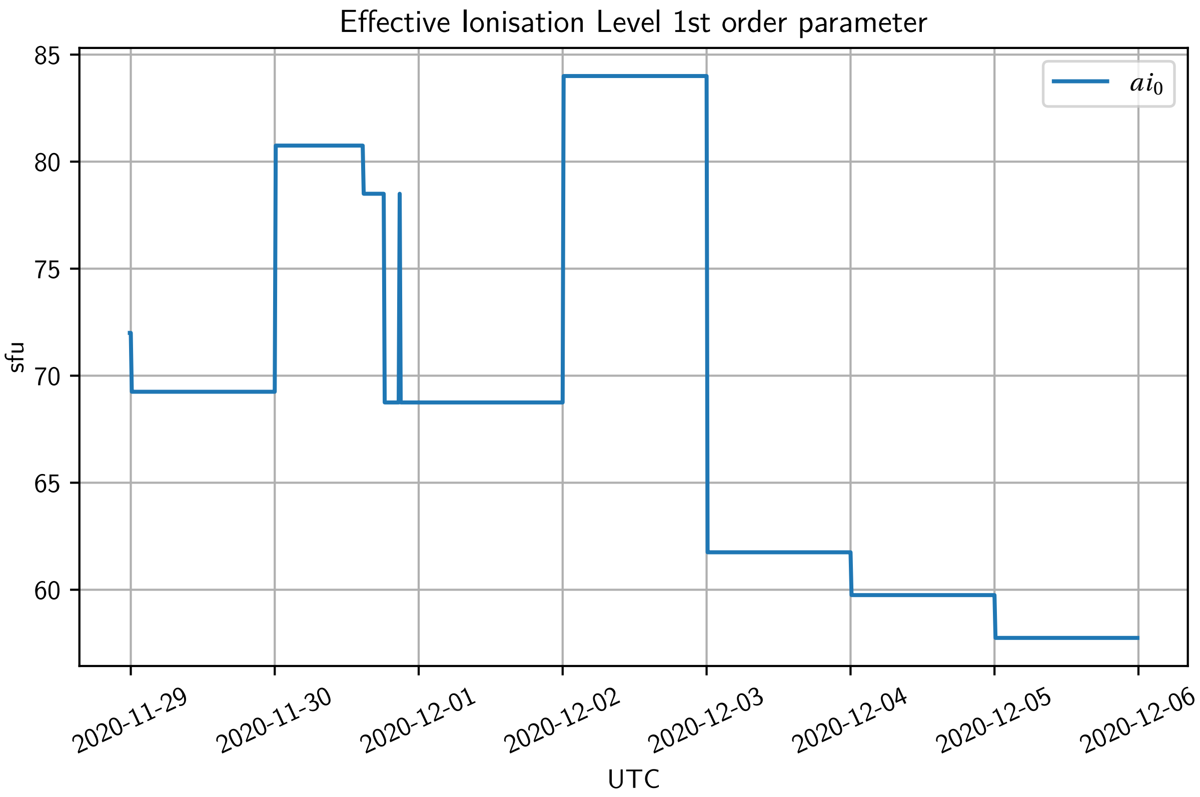

EXPERIMENTAL: Mean observed time offset between Galileo, GPS and BeiDou
GPS
BeiDou
nanoseconds
12
10
8
6
4
2
0
-2
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

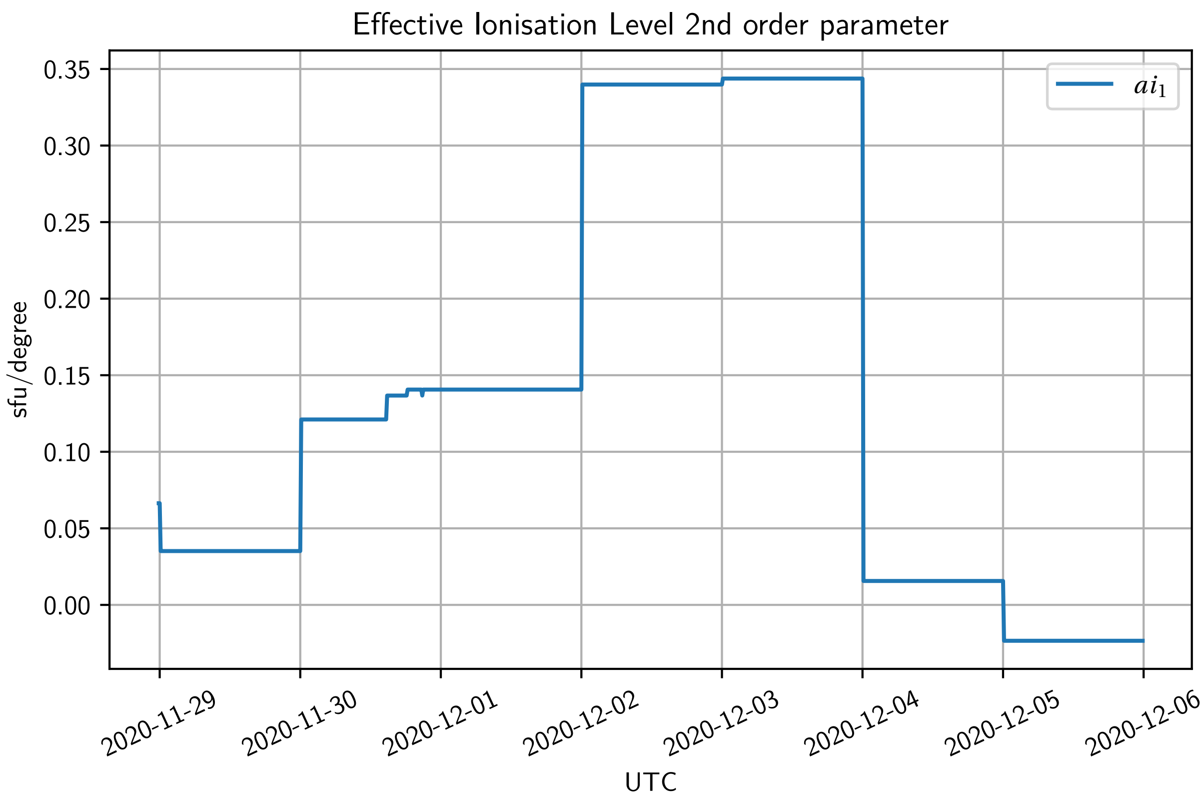

EXPERIMENTAL: Mean observed time offset between Galileo and GLONASS
GLONASS
nanoseconds
46
44
42
40
38
36
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

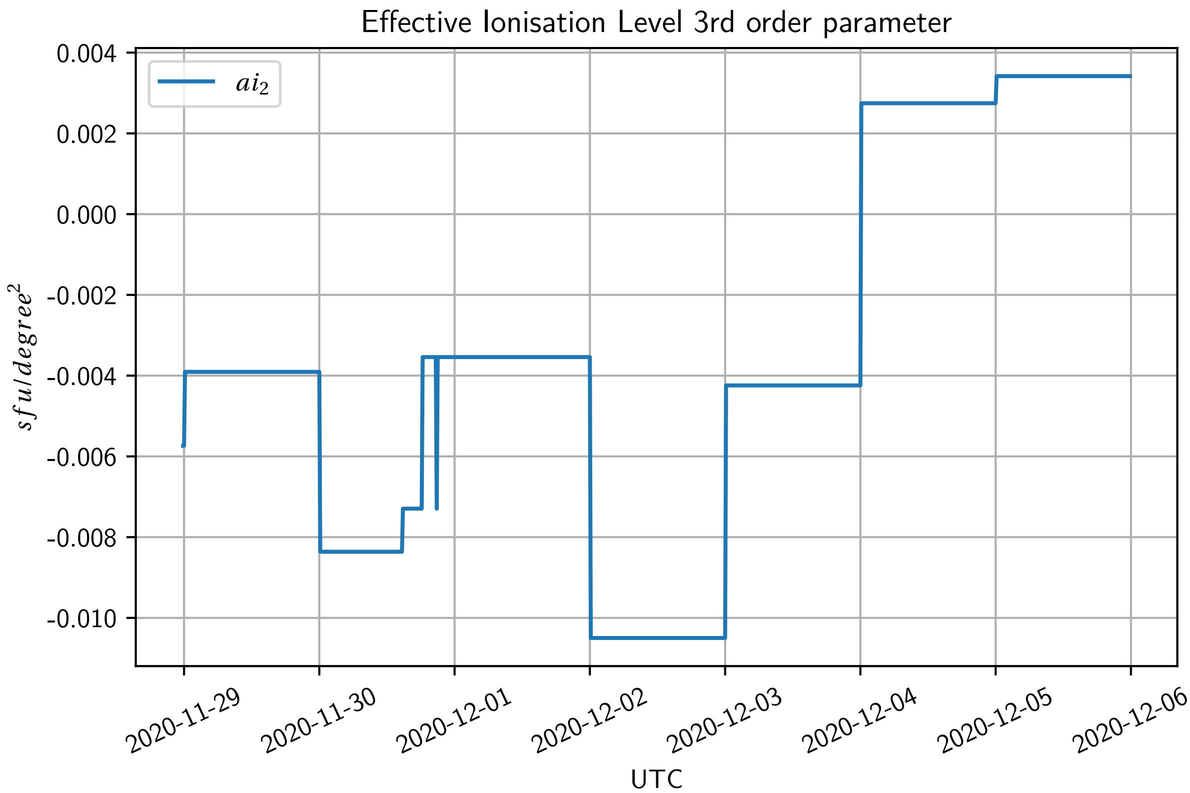
Chapter 9

Ionosphere

For the benefit of single-frequency receivers, Galileo transmits parameters for an ionospheric delay model called "NeQuick G". The ai_0, ai_1 and ai_2 parameters describe the solar flux inputs for this model.







In these three graphs, a "thick" transition from one parameter level to another shows the time needed to propagate the new value to the entire constellation.

Dual-frequency receivers have no need for an ionospheric model since they can eliminate the ionosphere by combining multiple signals.

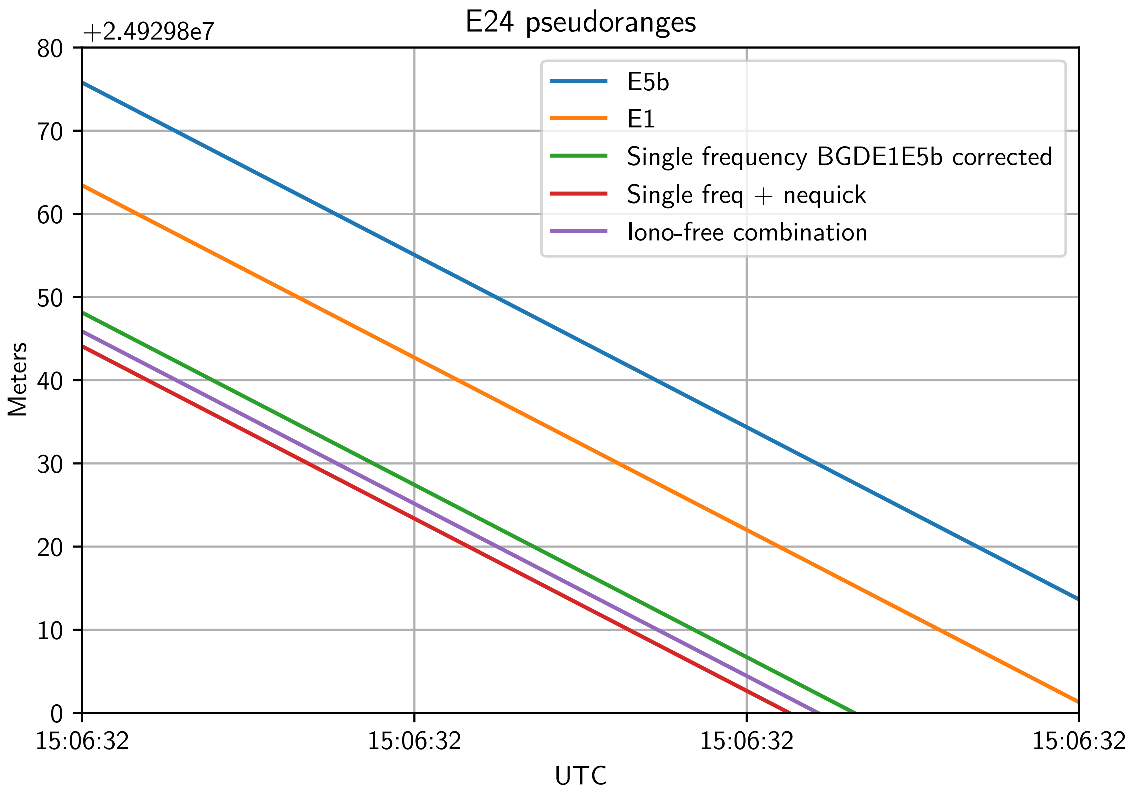
Future editions of this report will contain a graph that compares the the NeQuick G ionospheric delay model and the actual delays observed by our multi-frequency receivers.

9.1 NeQuick G analysis

This analysis is very preliminary and mostly shown to gather feedback, some of which has arrived already.

The NeQuick G code used was supplied by the Galileo Service Desk, and authored by the European Commission's Joint Research Centre. While open source, the code must be requested through a form. Those in a hurry may also find the code on GitHub, but it might be outdated.

For the analysis, a Ublox F9P receiver with an excellent reference center grade antenna is used, hosted in Delft, The Netherlands. This is the data we start with:



The top line represents the pseudorange of the E5b signal. The pseudorange is often close to the actual range to the satellite, but it must not be read this way. It is a measure of the relative Time of Receipt of the signal. Pseudoranges can be compared usefully, even if they are not absolute ranges.

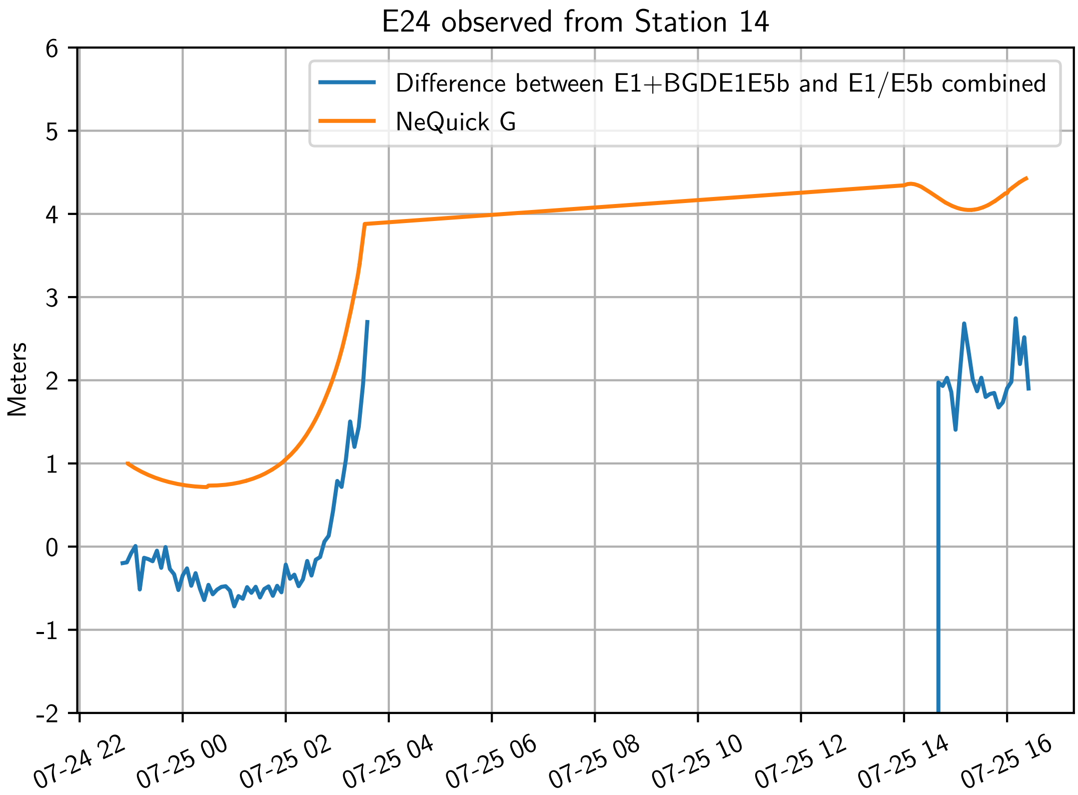
Below E5b is the E1 signal - it has a higher frequency, so it arrives earlier since it is delayed less by the ionosphere. This is explained at some length in this blog post. E24 also has an unusually large transmission gap between E1 and E5b making this graph visually very useful (thanks).

The E1 and E5b delays are combined to derive the ionosphere-free arrival time, which is the purple line. This is the "official clock", the one that a single-frequency receiver hopes to derive with the NeQuick G model.

A single-frequency receiver does so by adding the BGDE1E5b delay to the E1 pseudorange, and then it ends up at the green line, which is already quite close to the purple line (which is the goal).

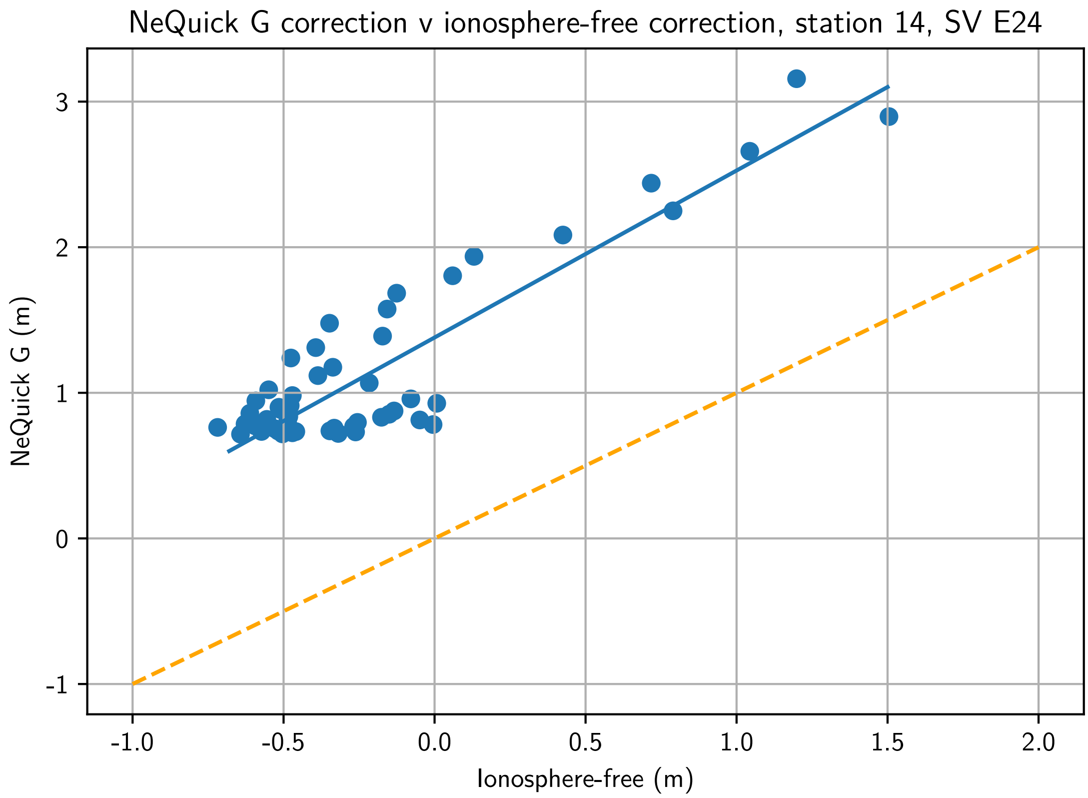
The receiver then calculates the ionospheric delay parameter using the NeQuick G model and supplied parameters, and uses that delay to end up at the red line, which is indeed quite close to the goal.

In this graph, the NeQuick G adjustment is compared to the 'calculated' ionospheric adjustment:



Note that E24 was measured during two disjoint periods. Model and "reality" clearly move in the same direction, with a gap. Note that the measured ionospheric correction is *negative* at times, which should not be possible.

In histogram form:



This shows great correlation between NeQuick G and the measured ionospheric correction, albeit at an offset.

Combined with our observed negative ionospheric correction, this likely means our data, measurements and processing still has errors in there.

It is however already good to see the great correlation between measurement and model.

Chapter 10

COSPAS-SARSAT Return Link Messages

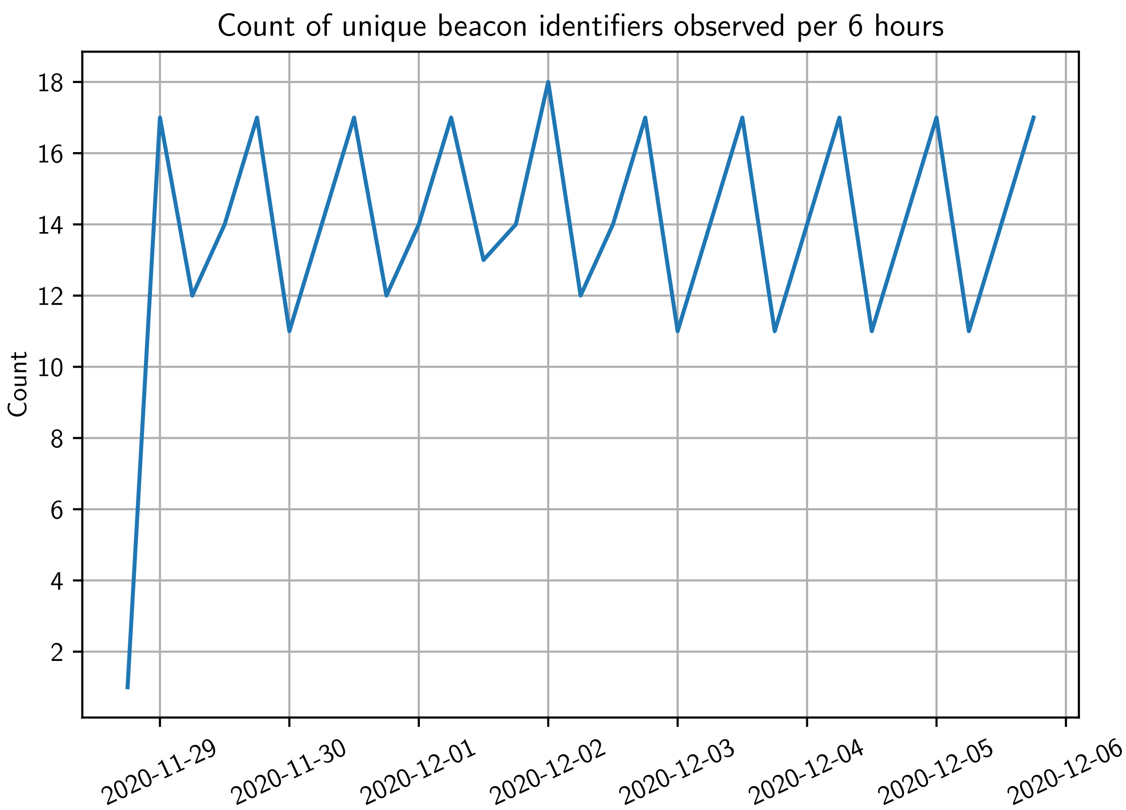
Galileo satellites carry a Search And Rescue beacon payload which can pick up distress signals and alert authorities. Uniquely, Galileo also provides a Return Link Service by which the beacon can receive confirmation its request for help has been processed.

The Galmon.eu network sees Return Link Messages (RLMs), but does not report on the associated beacon identifiers, as these identify people and vessels with actual emergencies.

We can however publish statistics of RLM traffic. It is known that five test beacons are used to verify correct operations, and these five are normally always observed.

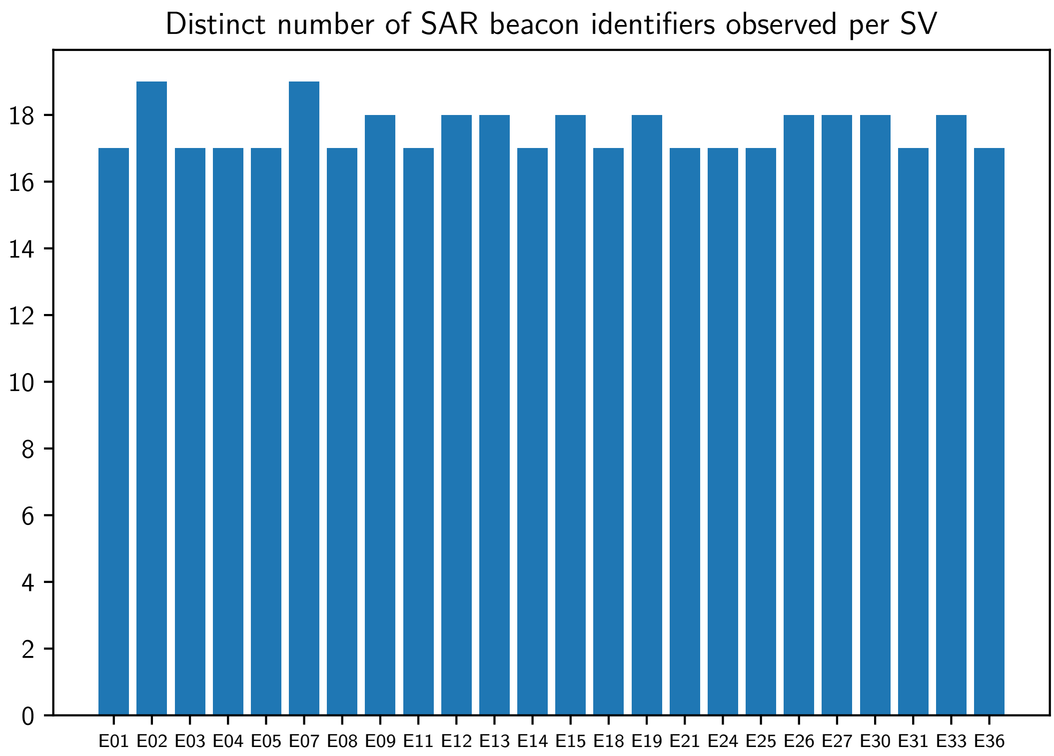
RLM frames are frequently received by dozens of our receivers, so it does not make sense to plot the raw number of received messages, since it is hard to tell which are duplicates.

This graph shows the number of unique beacon identifiers identified per six hour period, which normally always includes the five known testing beacons:



It is normal for this graph to drop off near the right, where the reporting period ends.

Not all satellites appear to have equal SAR RLM capabilities, here is a graph of number of unique beacon identifiers seen per SV over the reporting period:



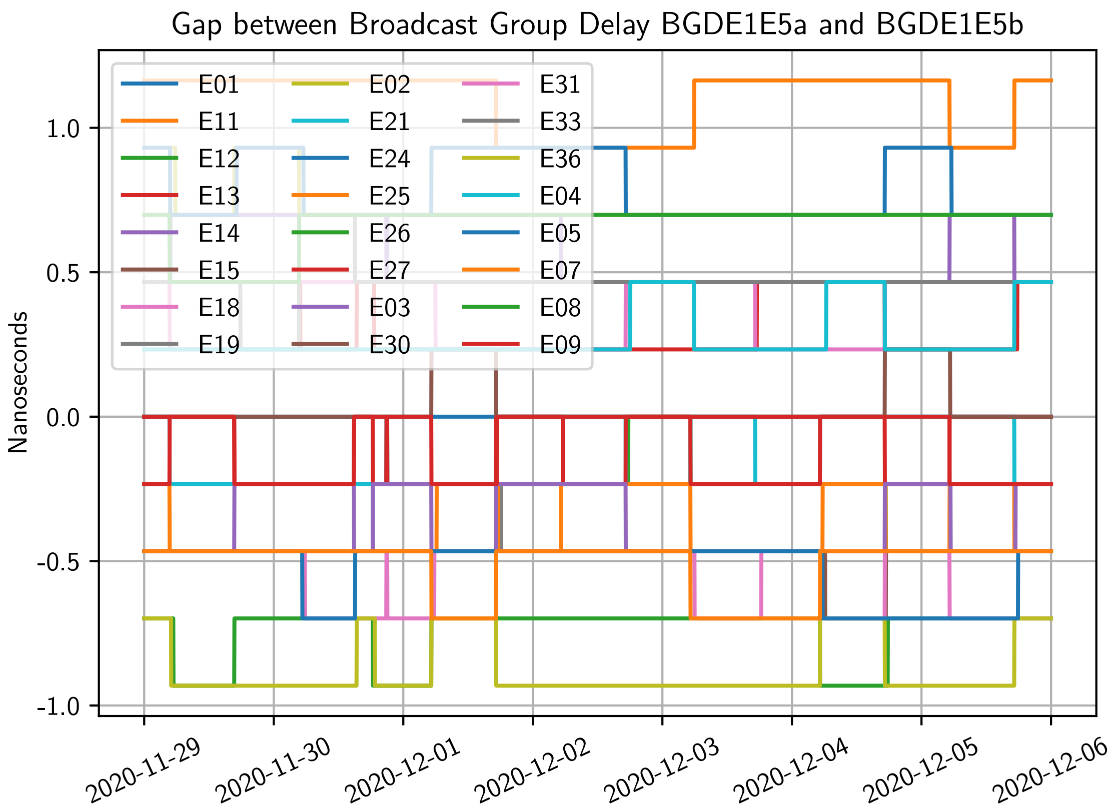
Chapter 11

Other parameters

11.1 BGD E1E5a, E1E5b

This plots the difference between the E1E5a and E1E5b parameters, which should correspond to the gap between the af_0 values broadcast over E1/E5b (I/NAV) and E5a (F/NAV).

This graph incidentally also describes the correction this report applies to the NAVCAST RTCM SSR data to undo the I/NAV-F/NAV modification.



Chapter 12

Per SV

The SP3 data as provided by GFZ Potsdam and ESOC refers to the Center of Mass (CoM) coordinates. The broadcast ephemerides however describe the trajectory of the Antenna Phase Centre (APC).

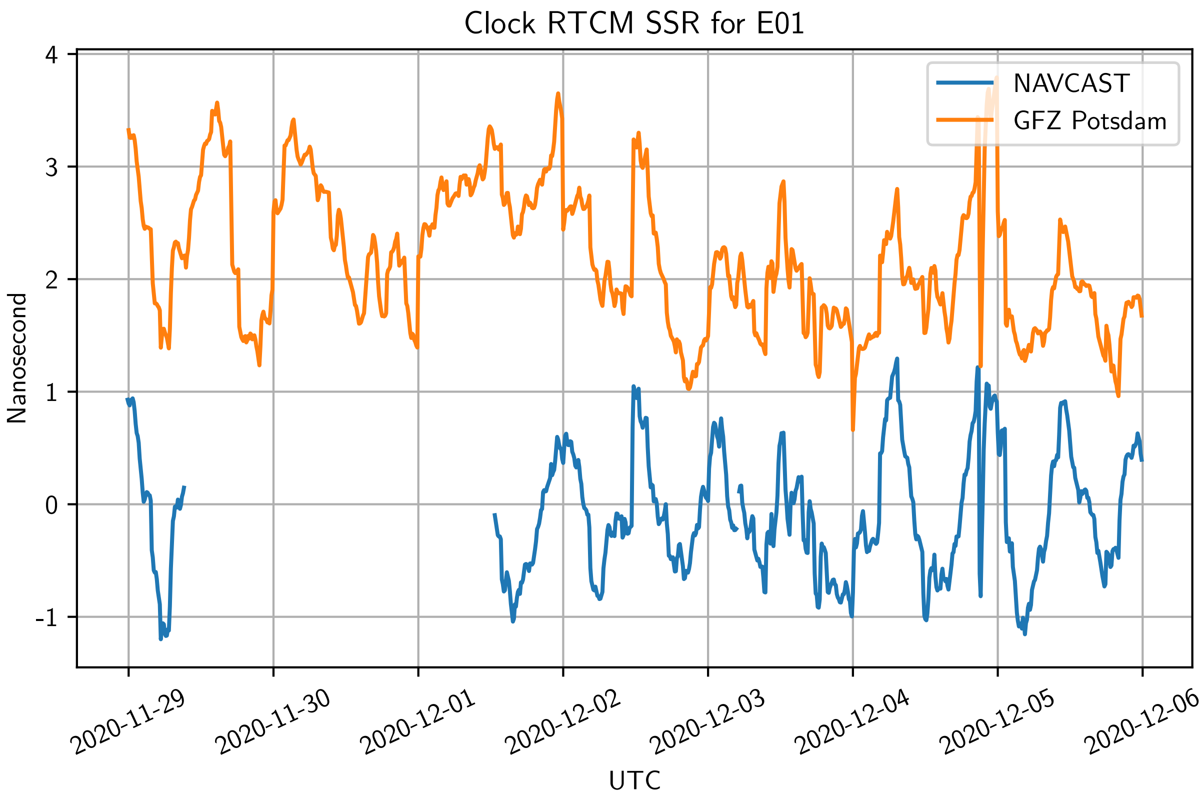
There is a measurable distance between CoM and APC, typically of around 80 centimeters.

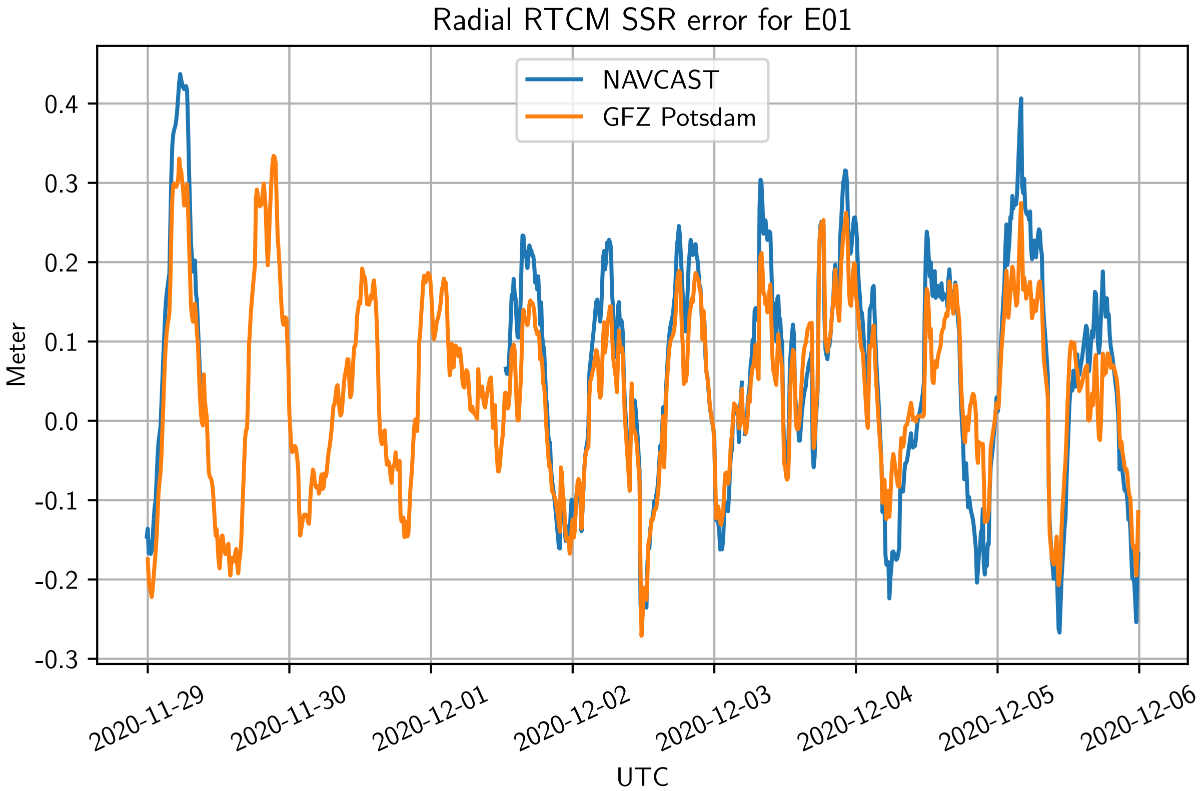
By using metrics provided by ESA for the Galileo satellites, it is possible to transpose the APC to the CoM via the Antenna Reference Point.

This transposition has so far proved to be too difficult for the authors of this report, but we have found the correction in the z-axis is 80 centimeters for most but not all SVs.

In future editions of this report, a more sophisticated correction will be applied. But for now, if SP3 data (GFZ or ESOC) is offset somewhat from the APC RTCM SSR data, this is why.

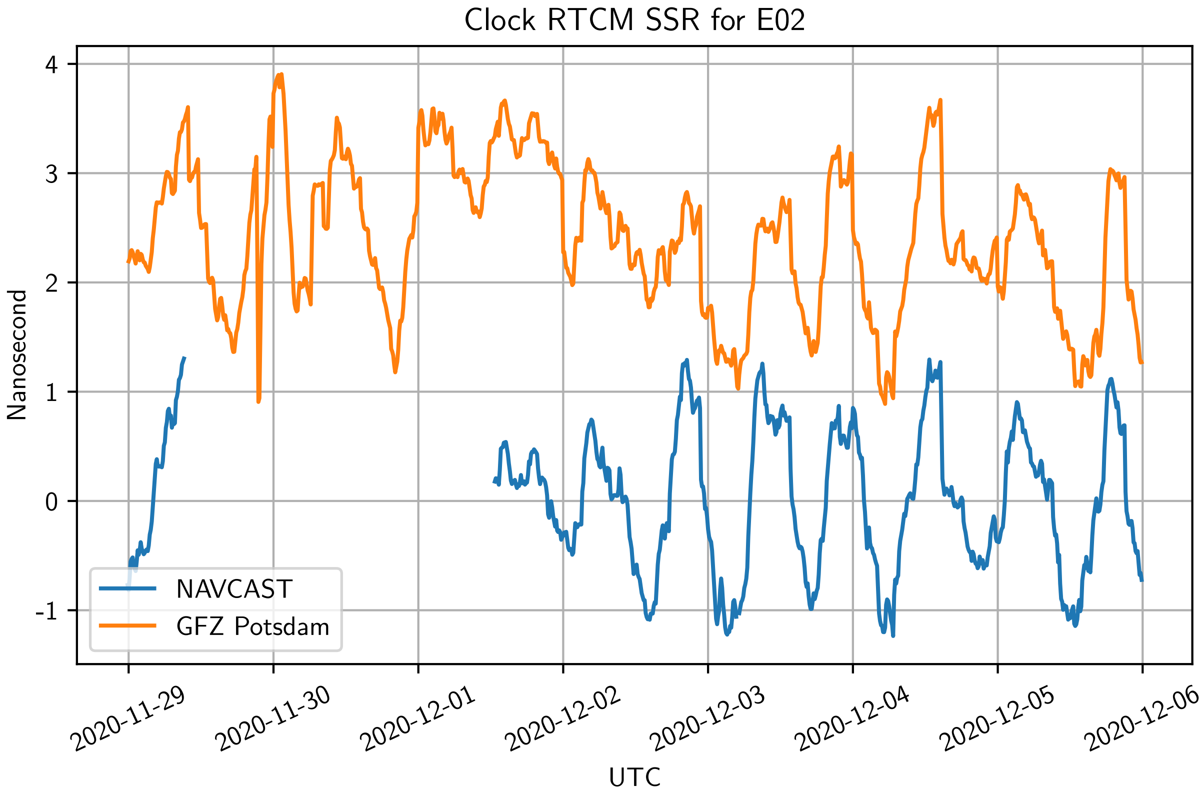
E01

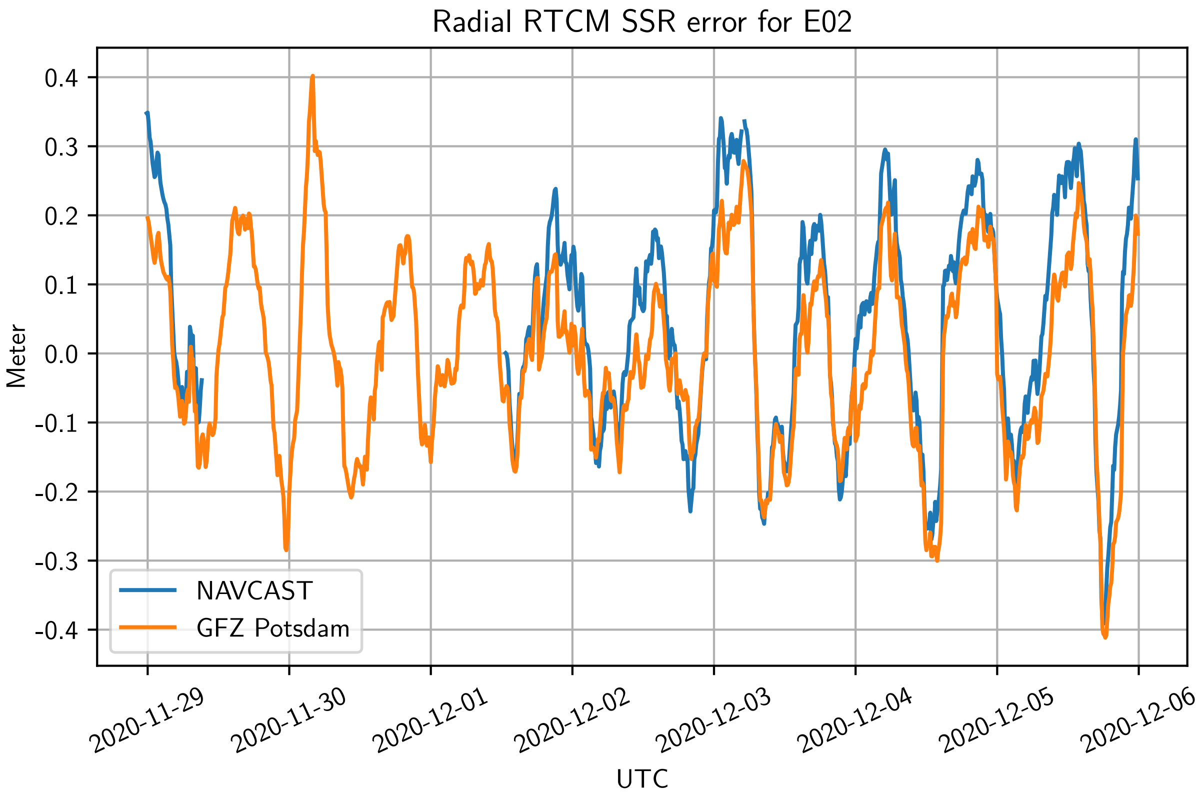




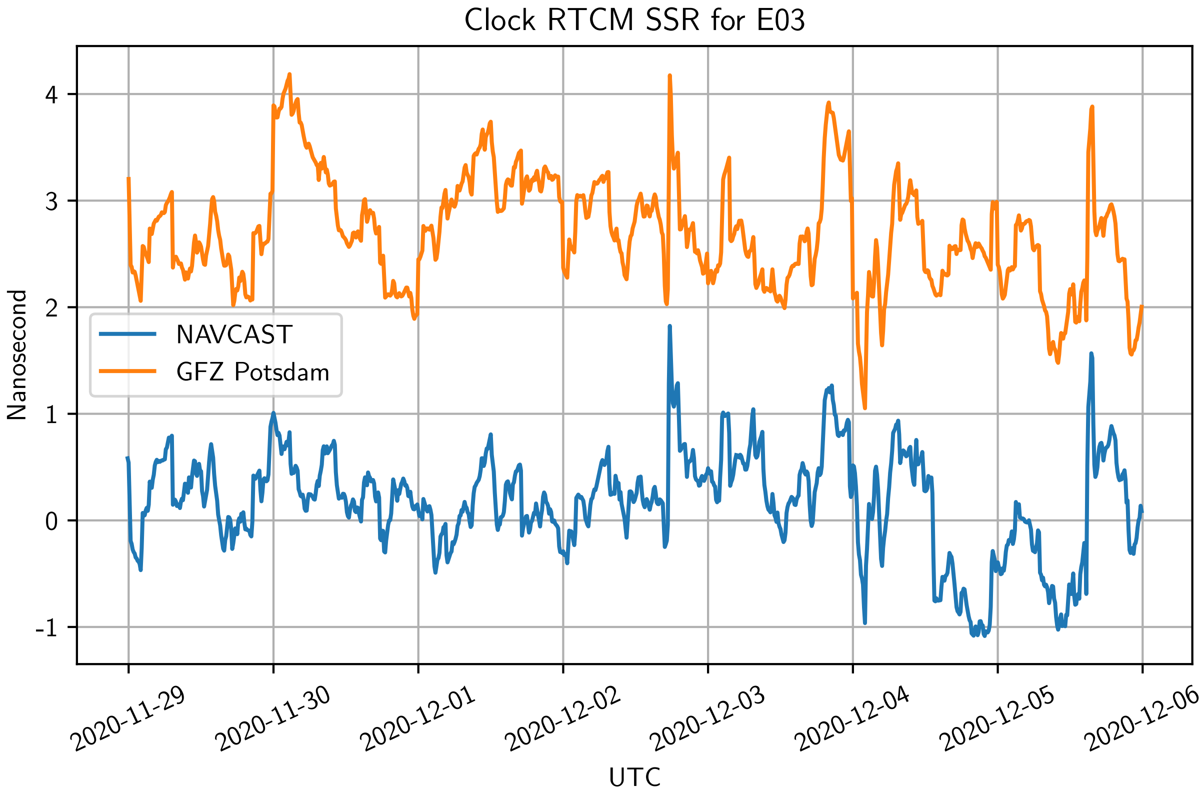
Radial RTCM SSR error for E01
NAVCAST
GFZ Potsdam
Meter
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

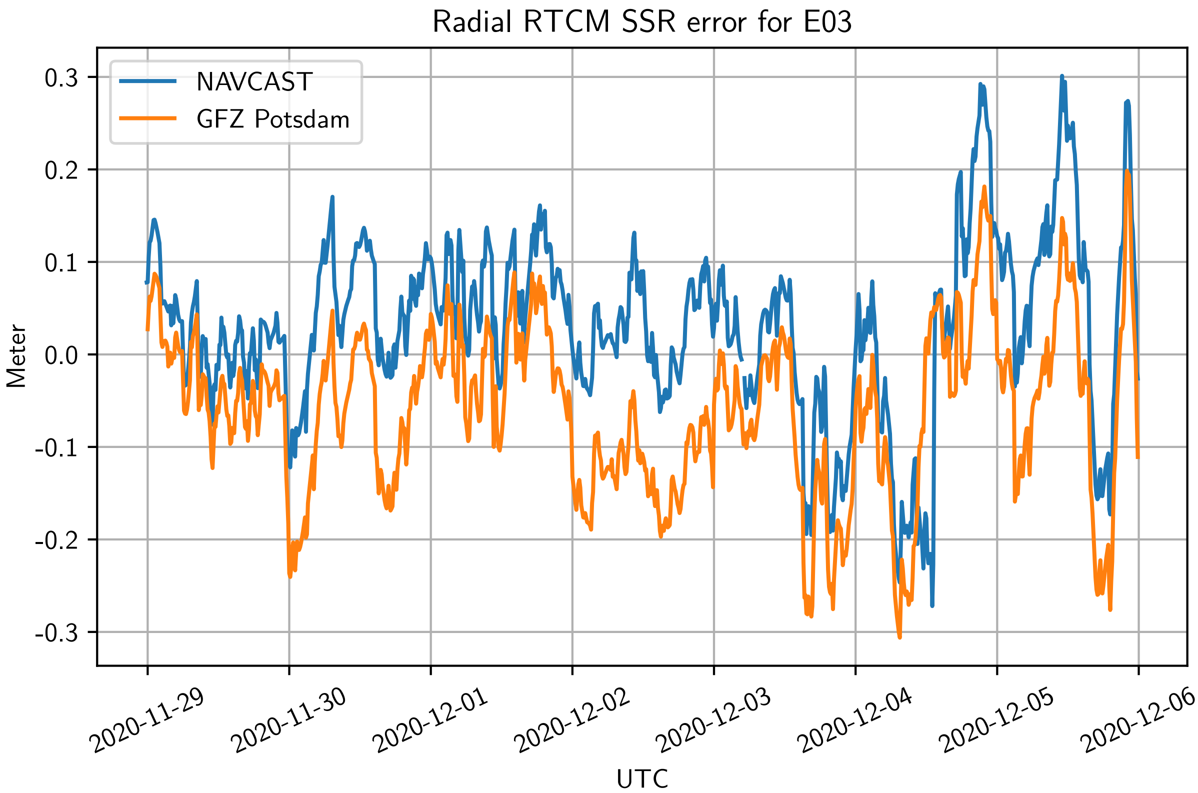
E02


Clock RTCM SSR for E02
Nanosecond
4
3
2
1
0
-1
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

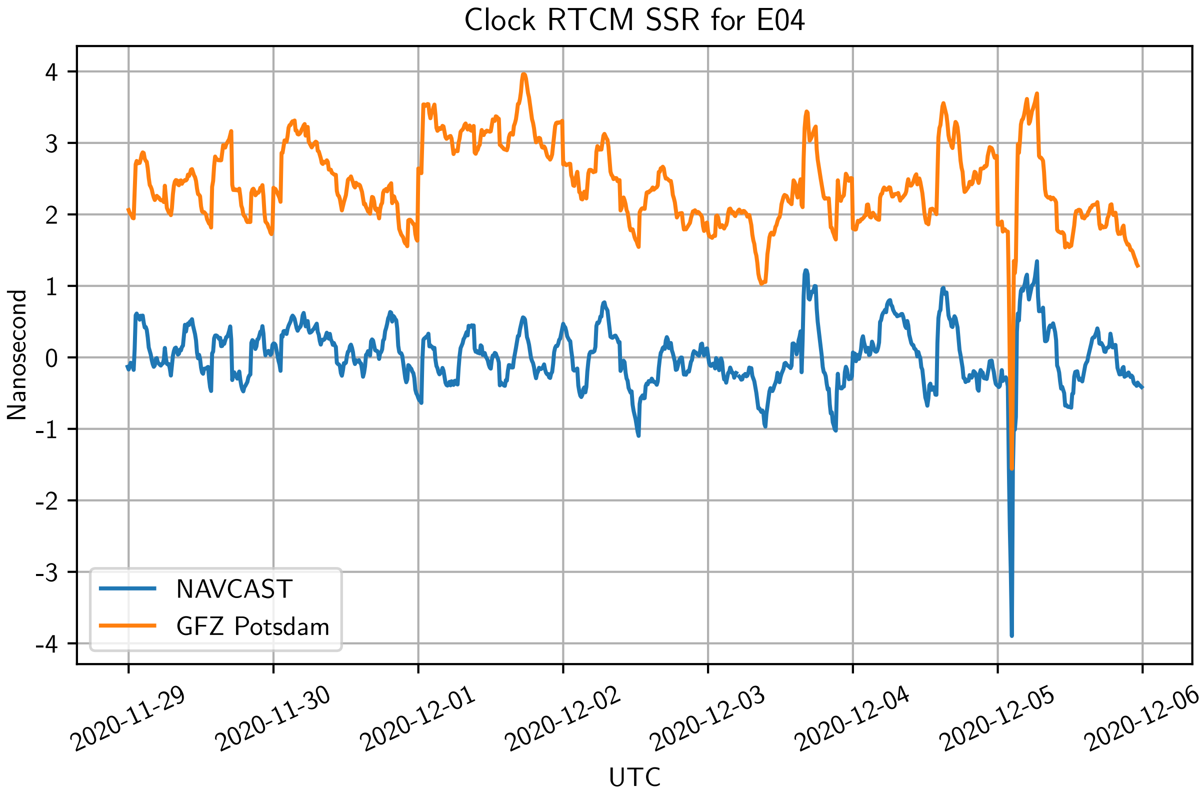

Radial RTCM SSR error for E02
Meter
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E03

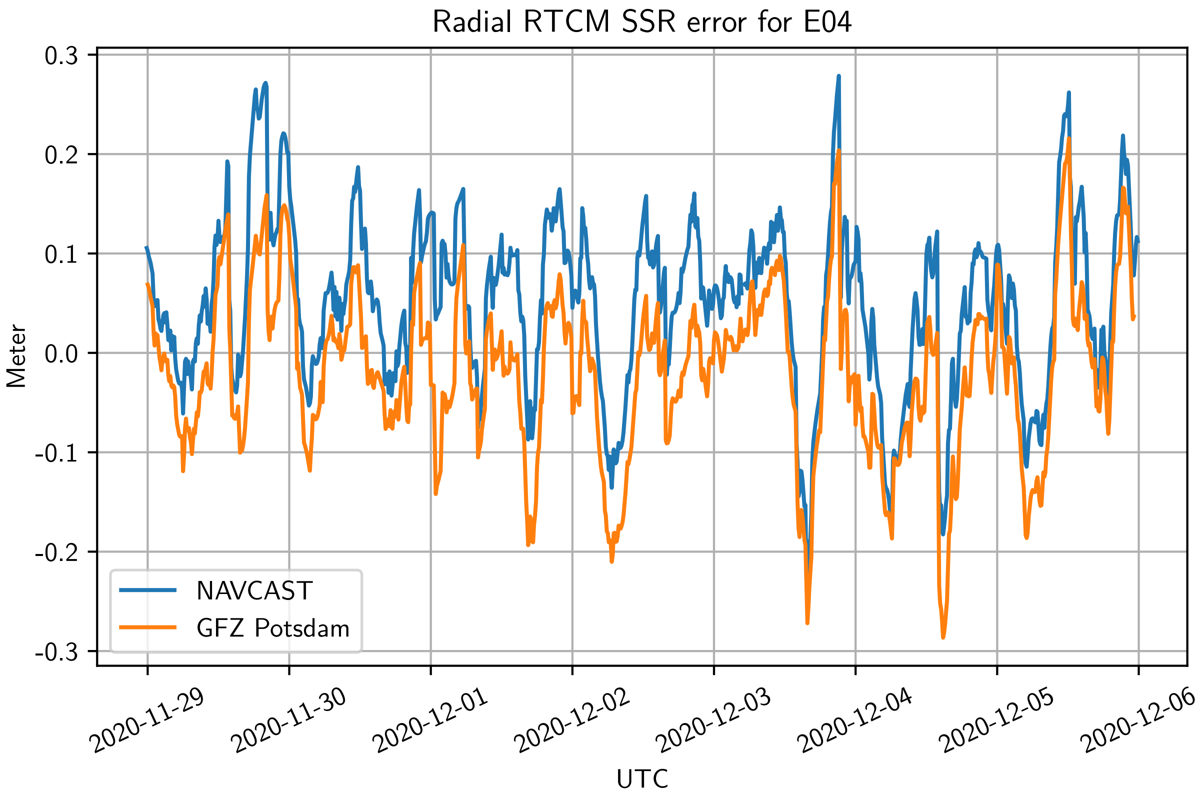

Clock RTCM SSR for E03
Nanosecond
4
3
2
1
0
-1
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC


Radial RTCM SSR error for E03
Meter
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E04

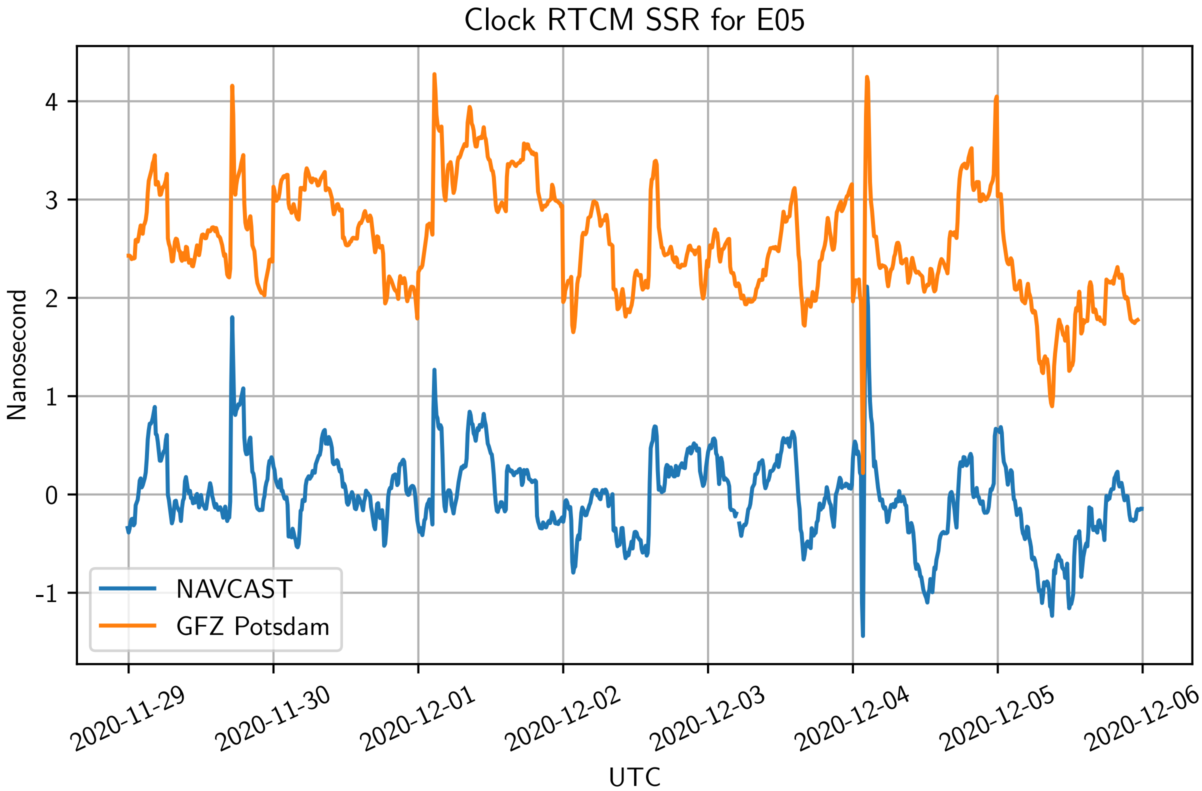


Clock RTCM SSR for E04
Nanosecond
4
3
2
1
0
-1
-2
-3
-4
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

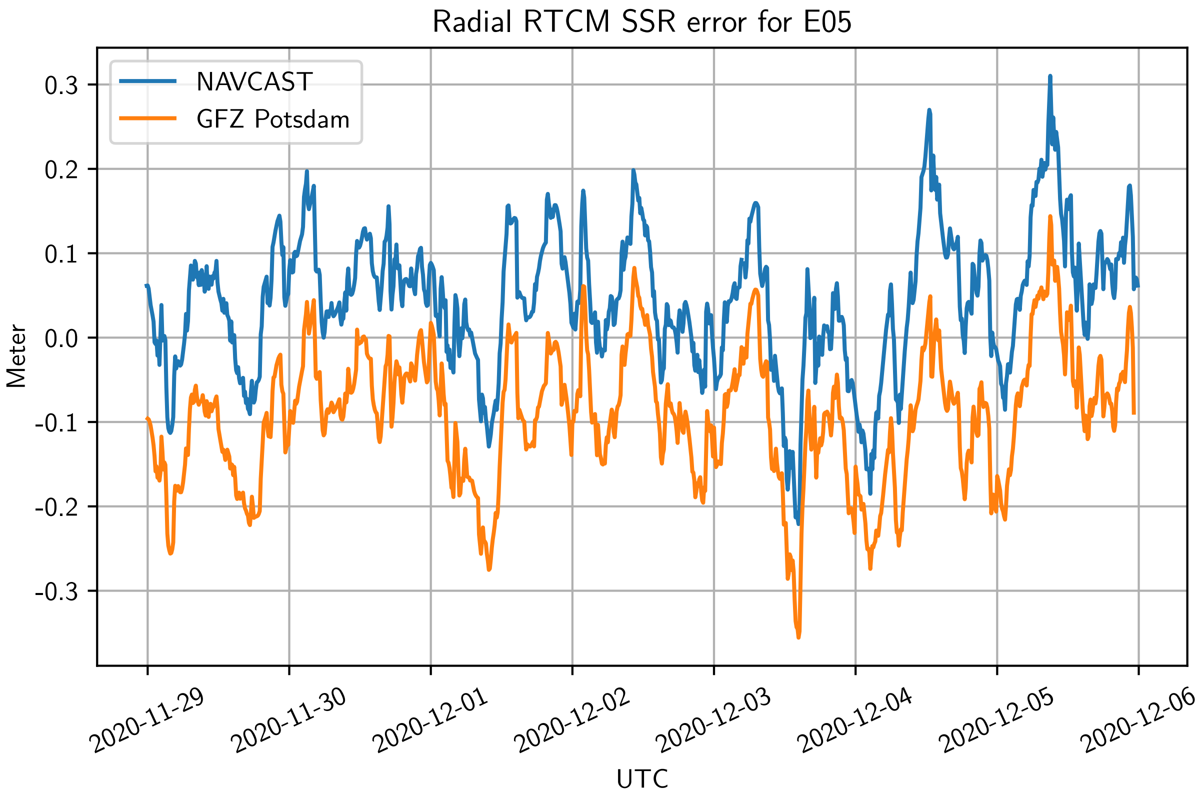


Radial RTCM SSR error for E04
Meter
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E05

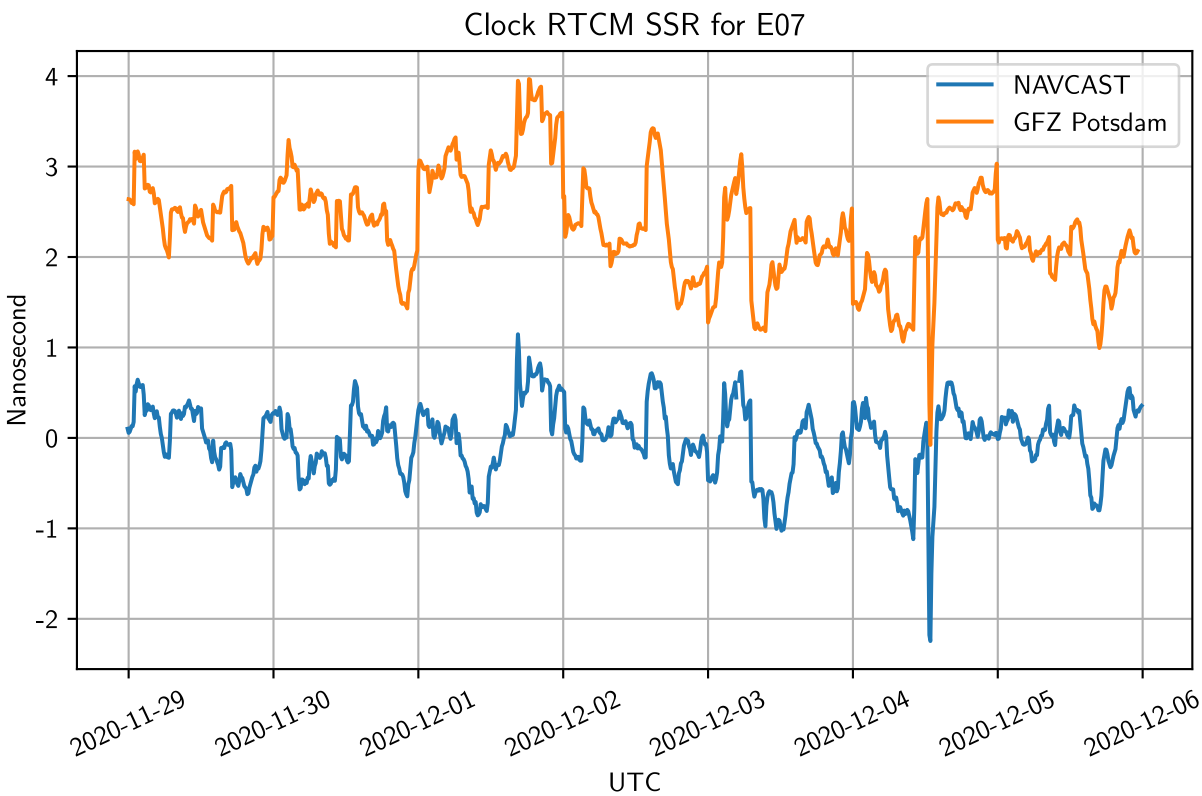


Clock RTCM SSR for E05
Nanosecond
4
3
2
1
0
-1
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

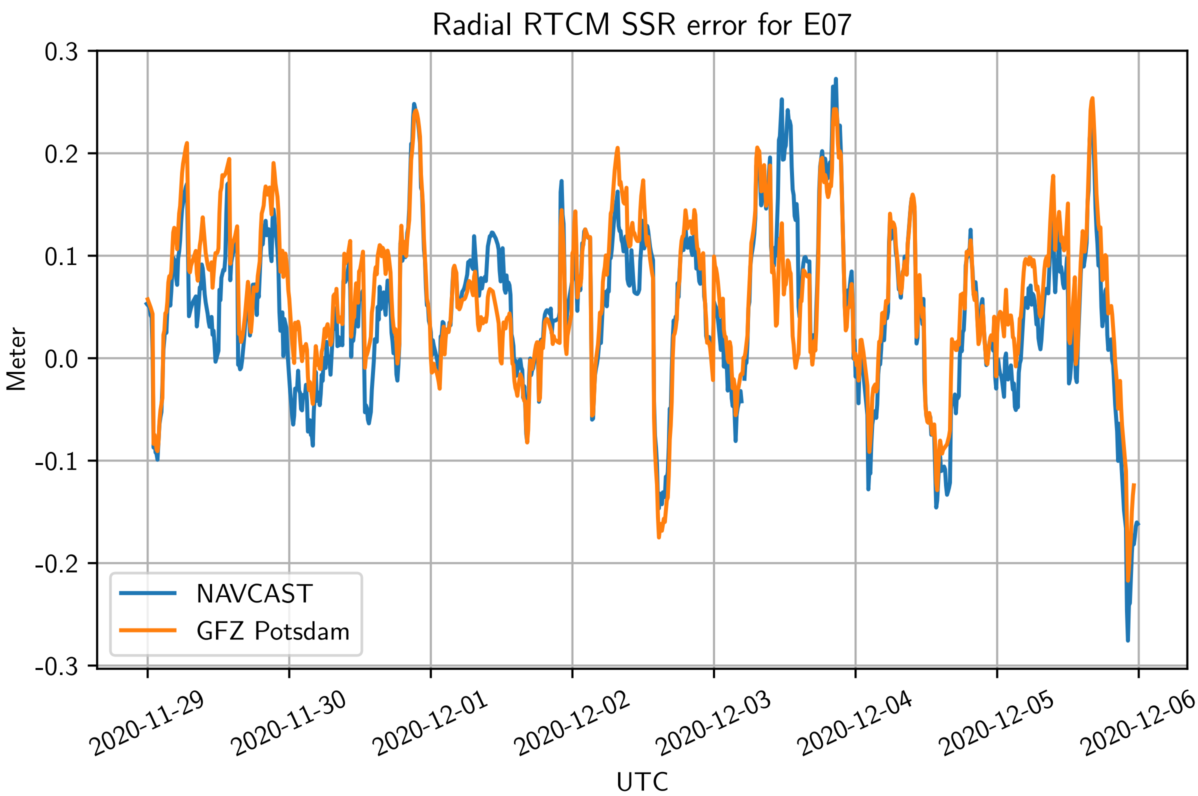


Radial RTCM SSR error for E05
Meter
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E07

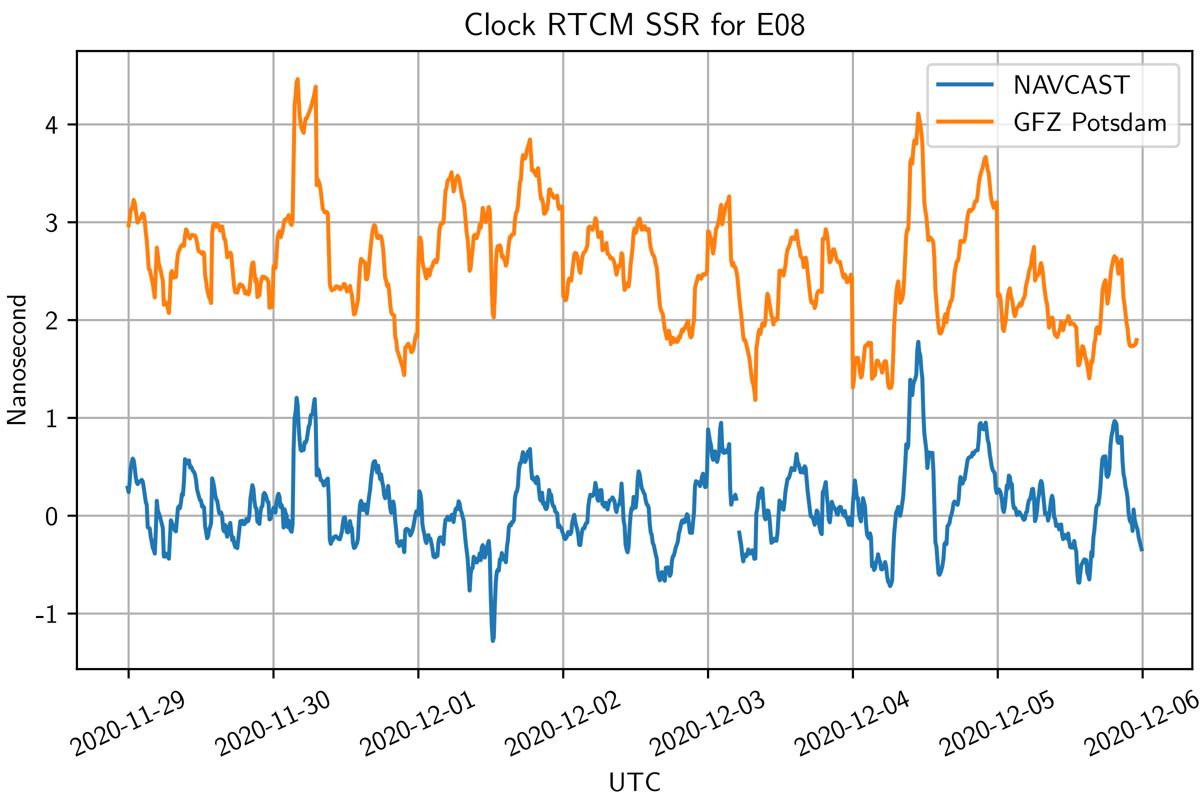


Clock RTCM SSR for E07
NAVCAST
GFZ Potsdam
Nanosecond
4
3
2
1
0
-1
-2
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

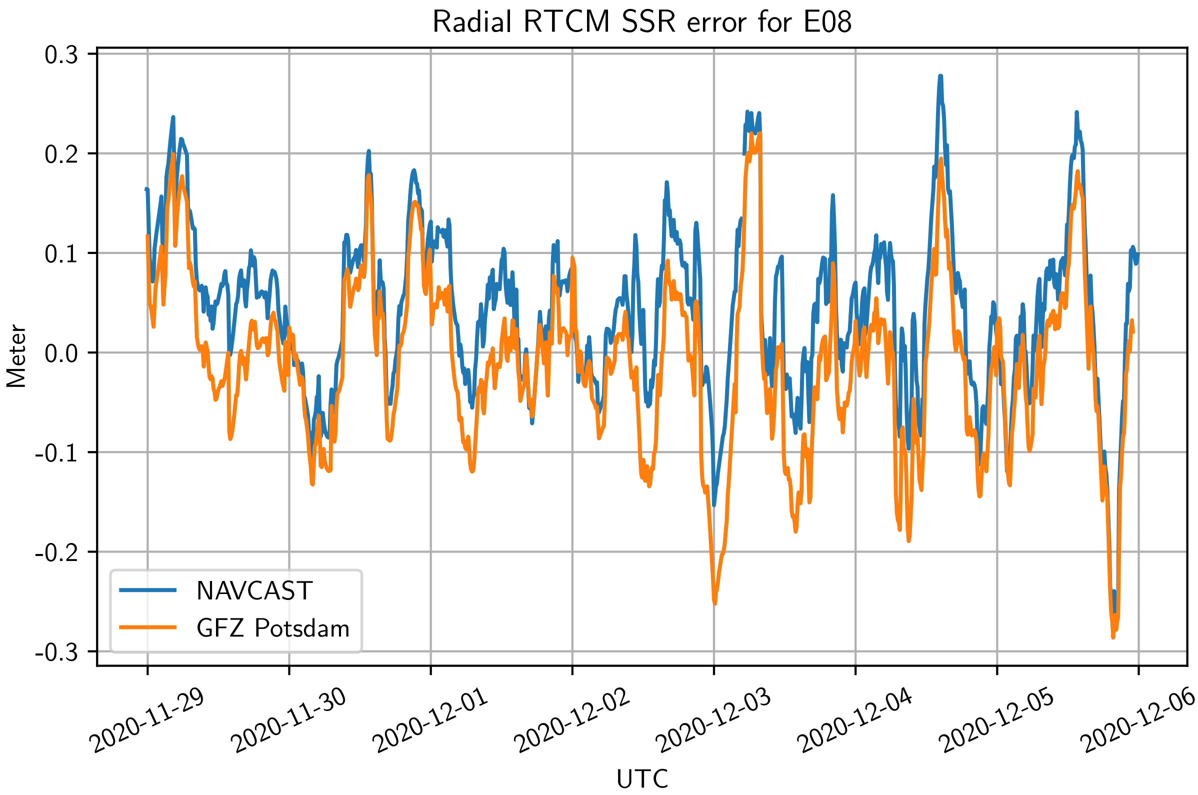


Radial RTCM SSR error for E07
Meter
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E08

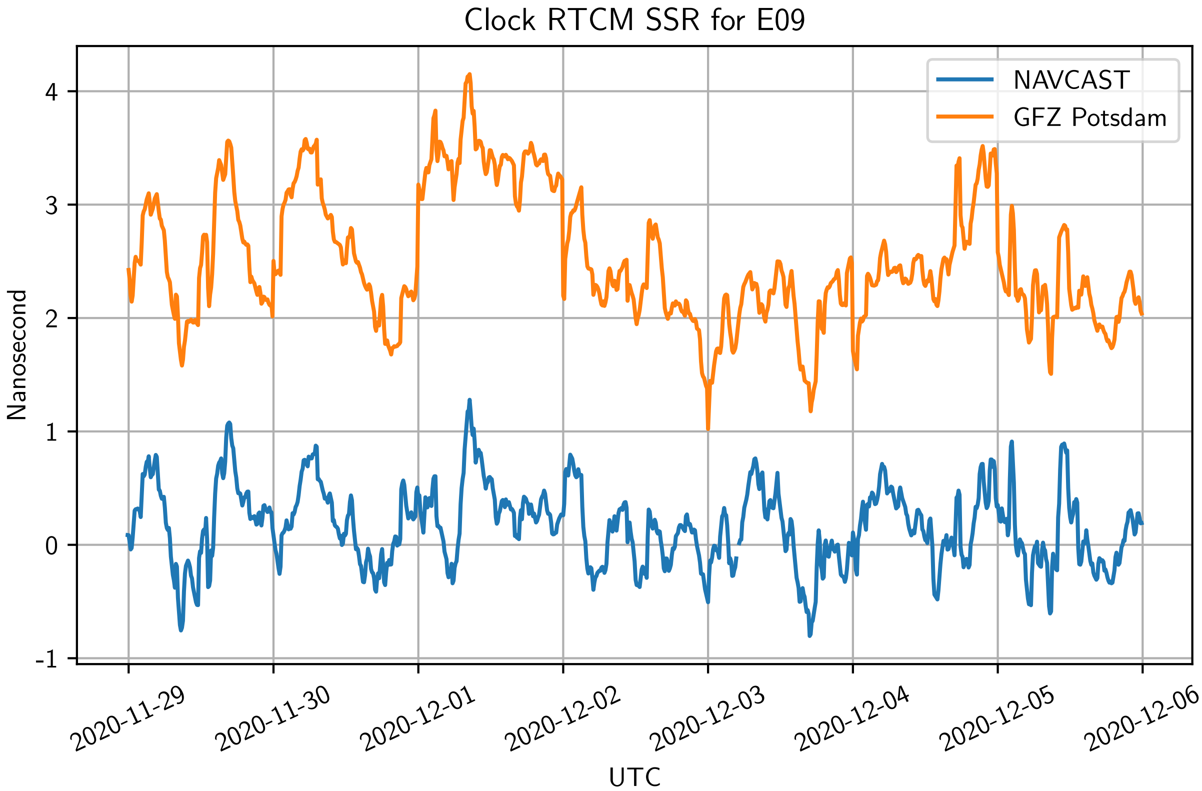


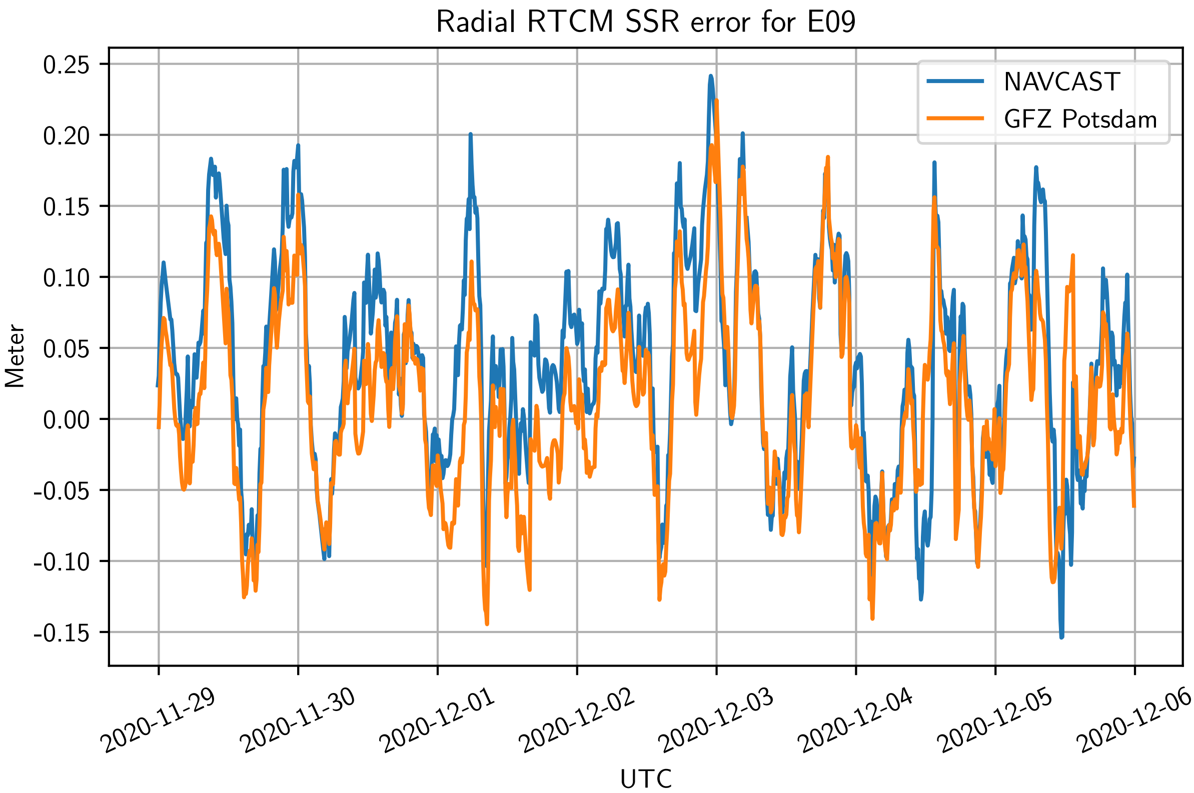
Clock RTCM SSR for E08
NAVCAST
GFZ Potsdam
Nanosecond
4
3
2
1
0
-1
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC



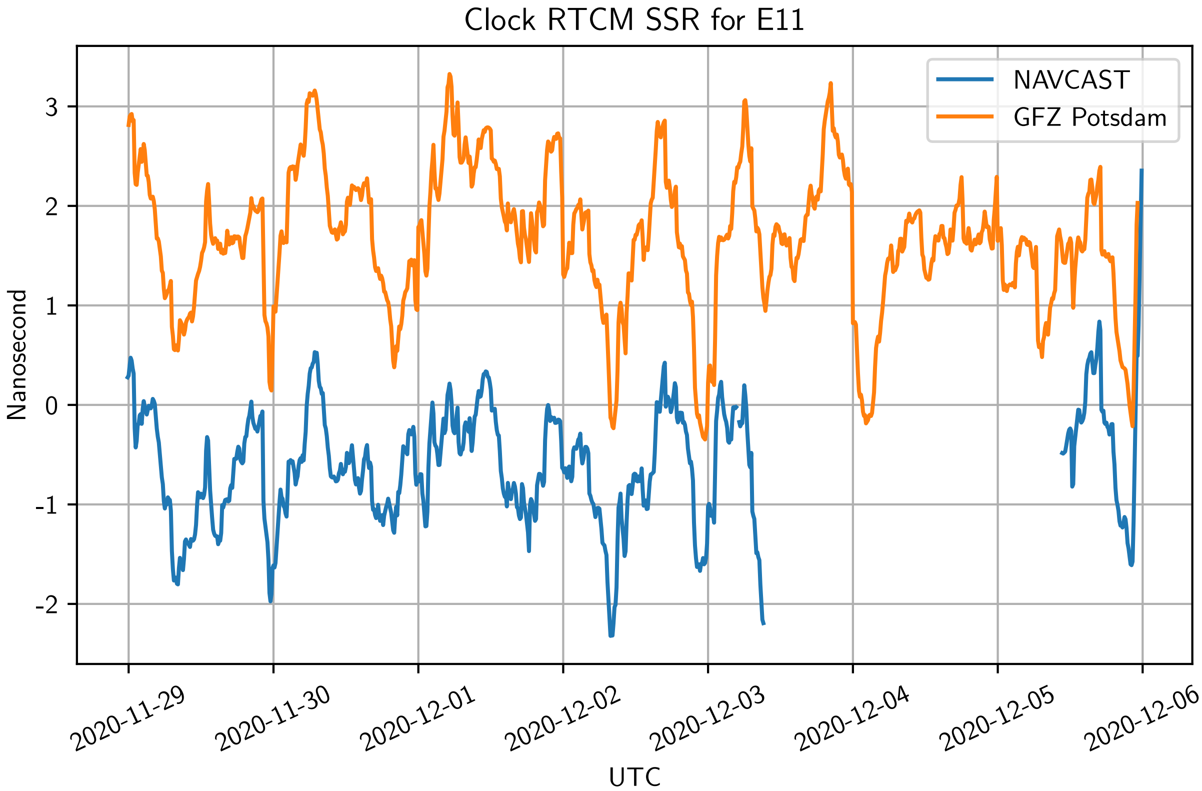
Radial RTCM SSR error for E08
NAVCAST
GFZ Potsdam
Meter
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

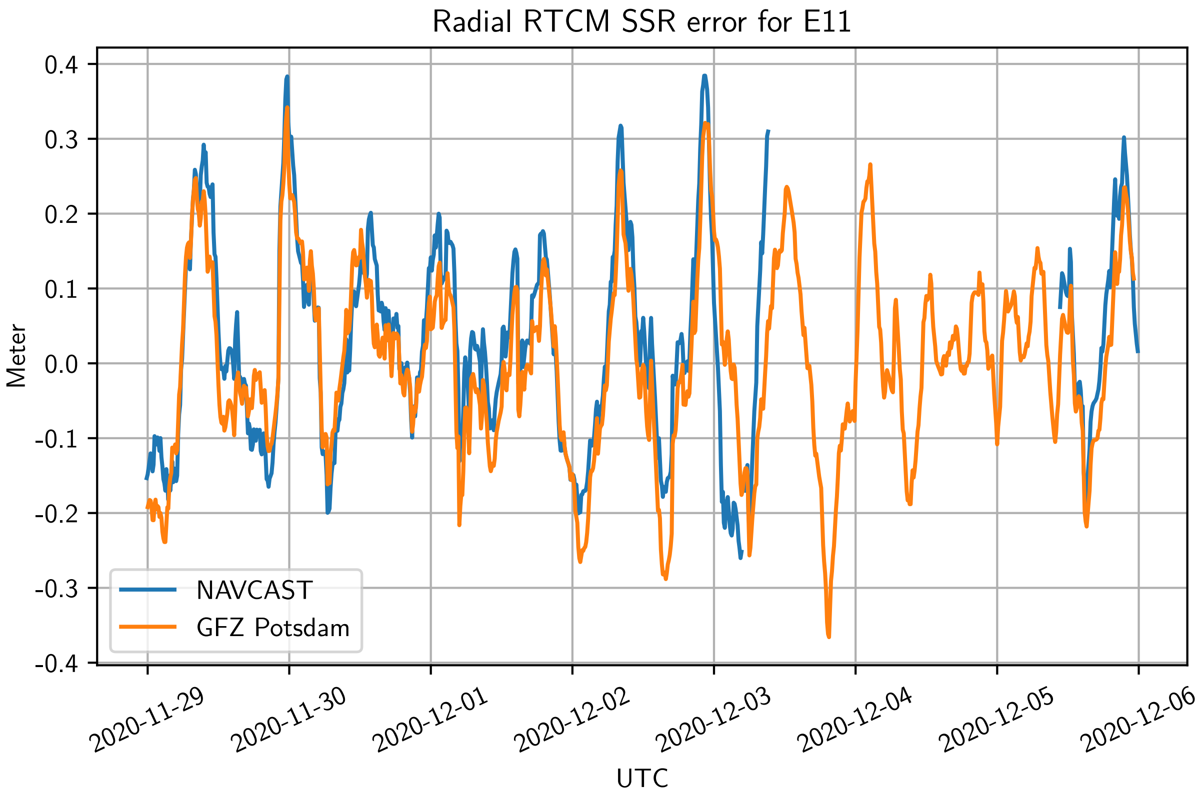
E09


Clock RTCM SSR for E09
NAVCAST
GFZ Potsdam
Nanosecond
4
3
2
1
0
-1
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

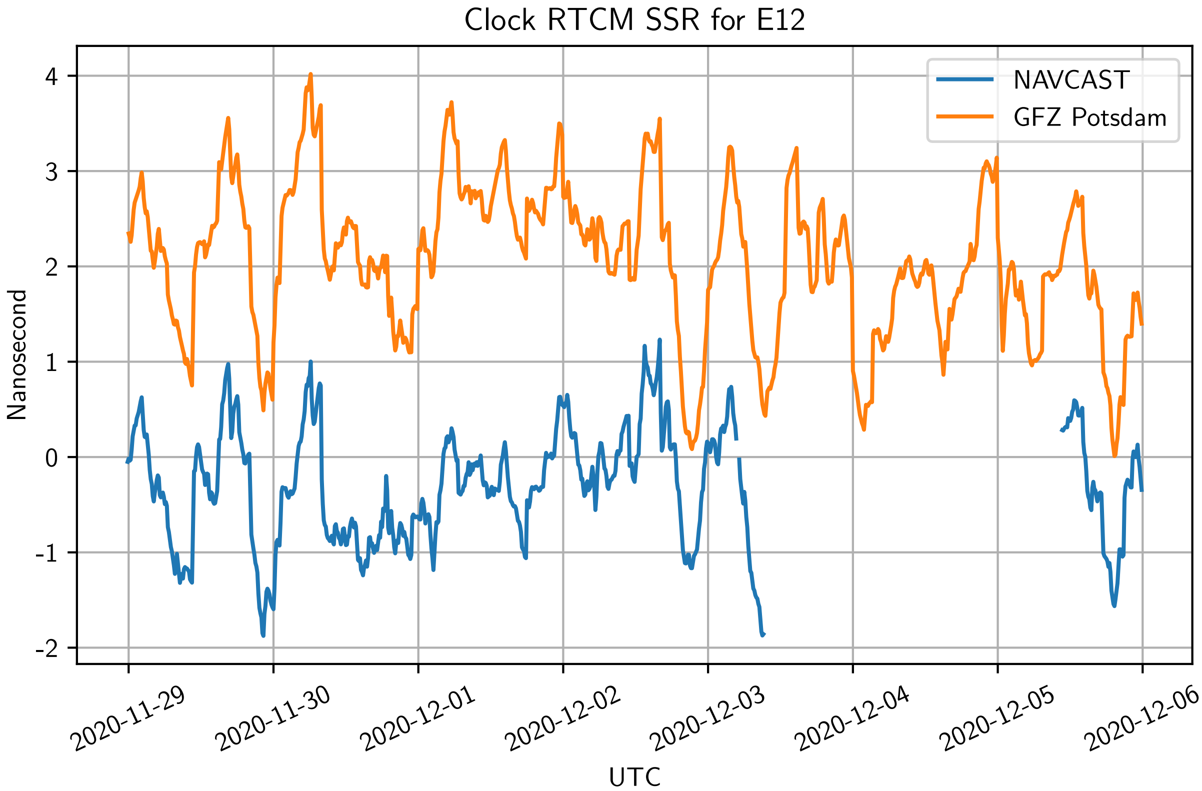

Radial RTCM SSR error for E09
NAVCAST
GFZ Potsdam
Meter
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

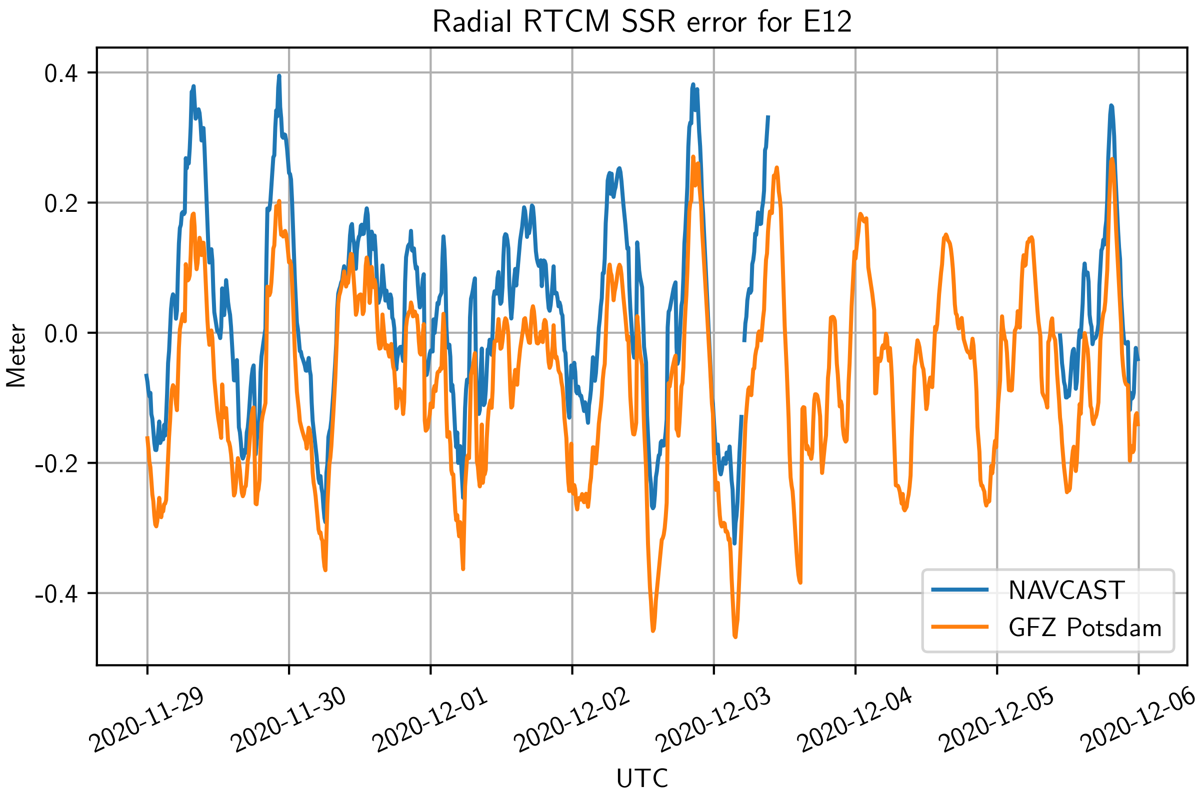
E11


Clock RTCM SSR for E11
Nanosecond
3
2
1
0
-1
-2
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

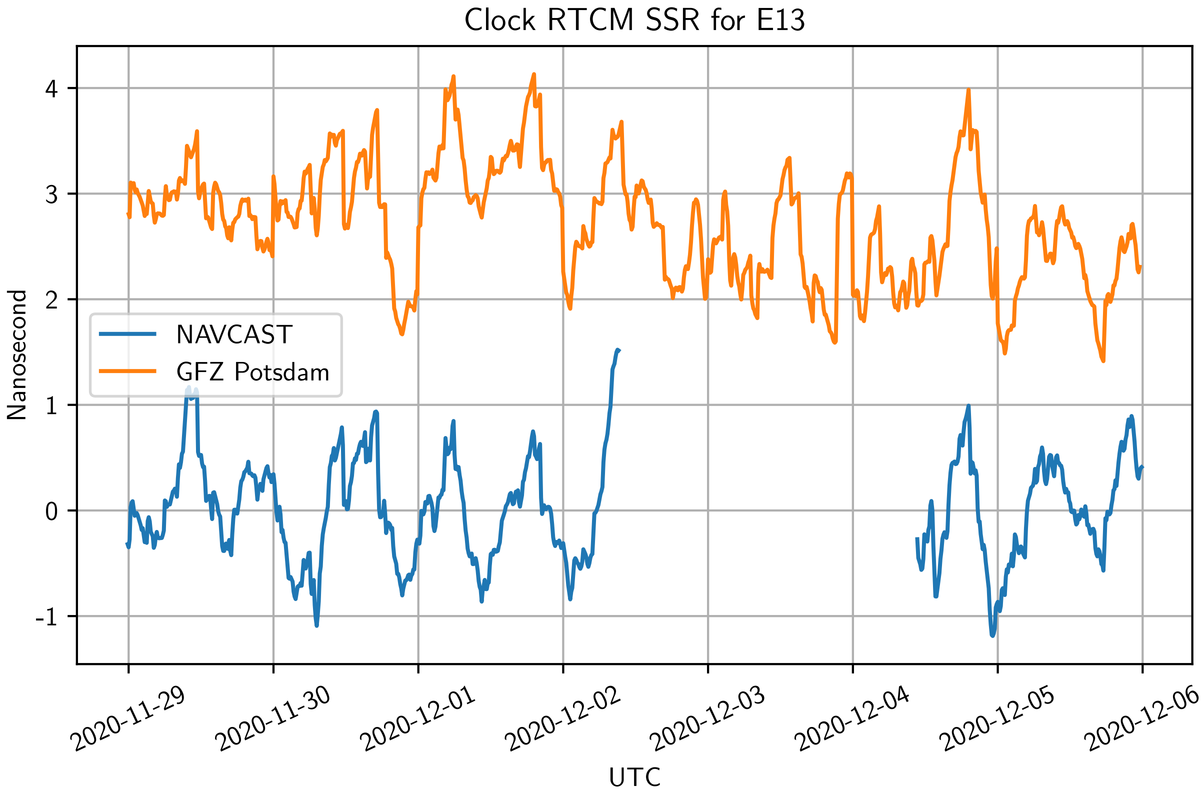

Radial RTCM SSR error for E11
Meter
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E12

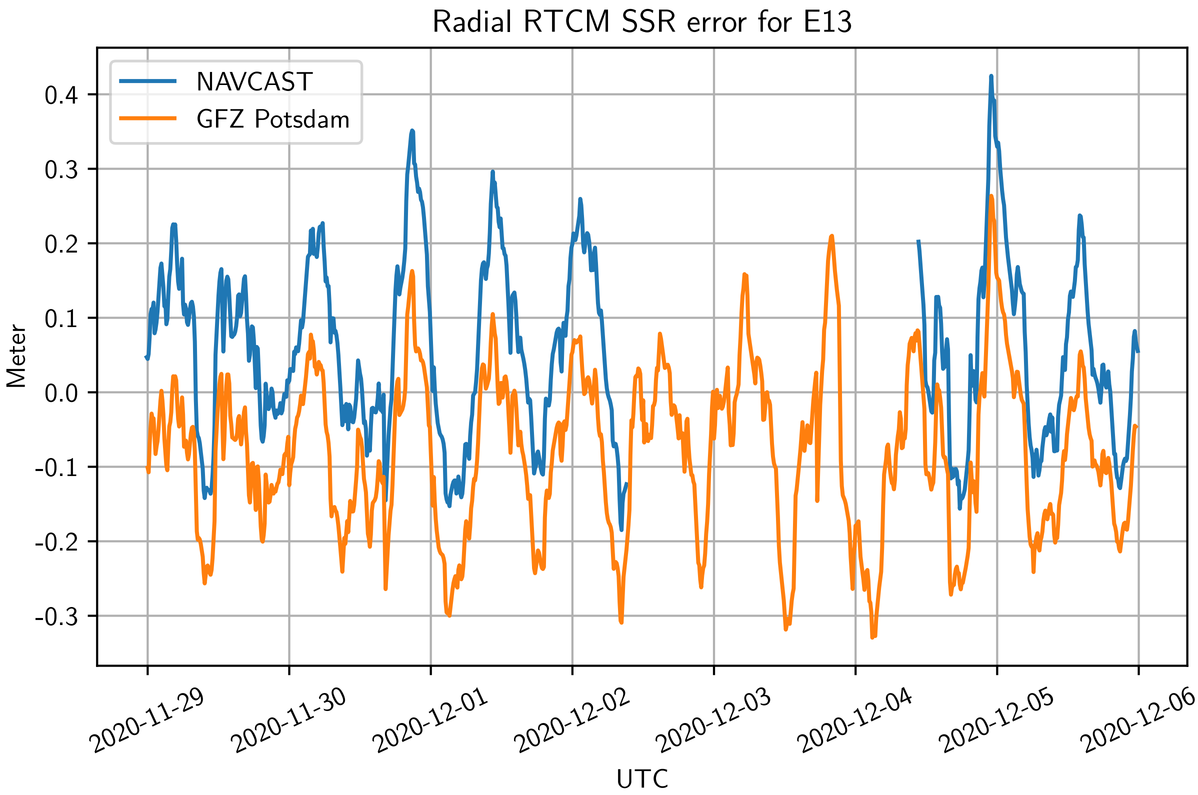

Clock RTCM SSR for E12
NAVCAST
GFZ Potsdam
Nanosecond
4
3
2
1
0
-1
-2
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC


Radial RTCM SSR error for E12
NAVCAST
GFZ Potsdam
Meter
0.4
0.2
0.0
-0.2
-0.4
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E13

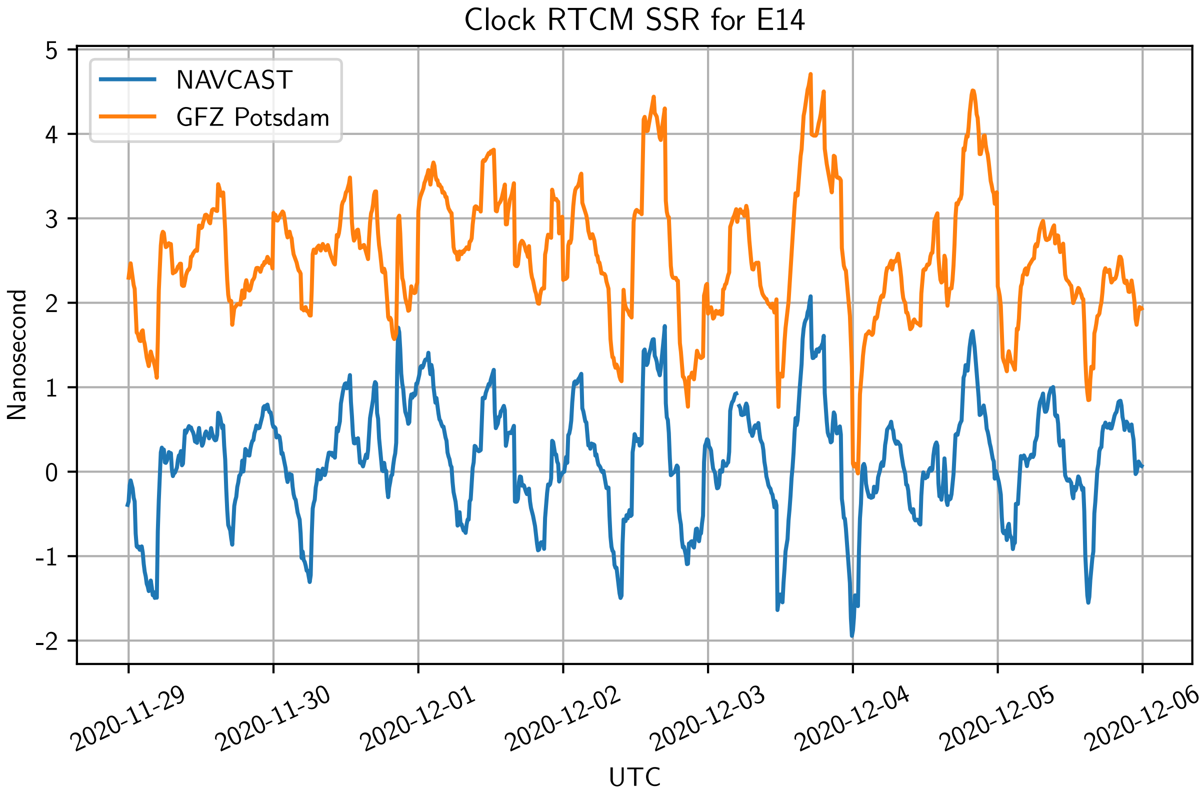


Clock RTCM SSR for E13
Nanosecond
4
3
2
1
0
-1
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

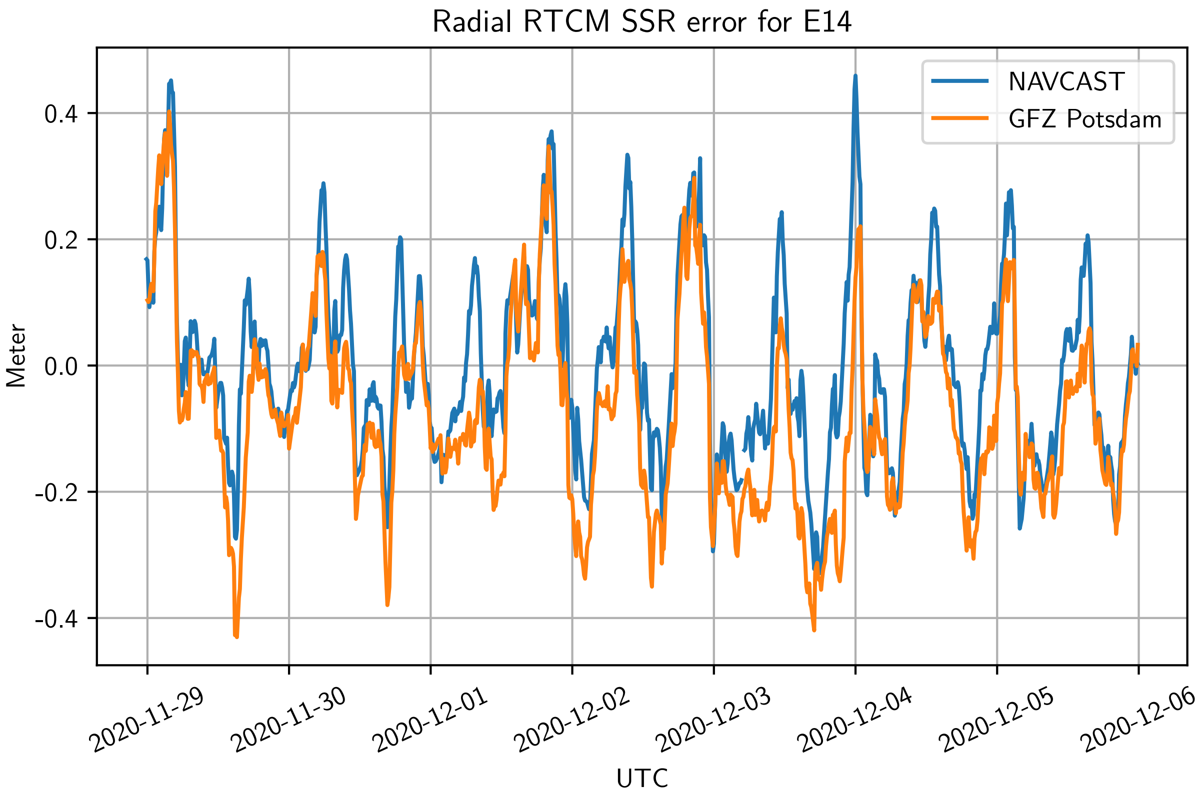


Radial RTCM SSR error for E13
Meter
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E14

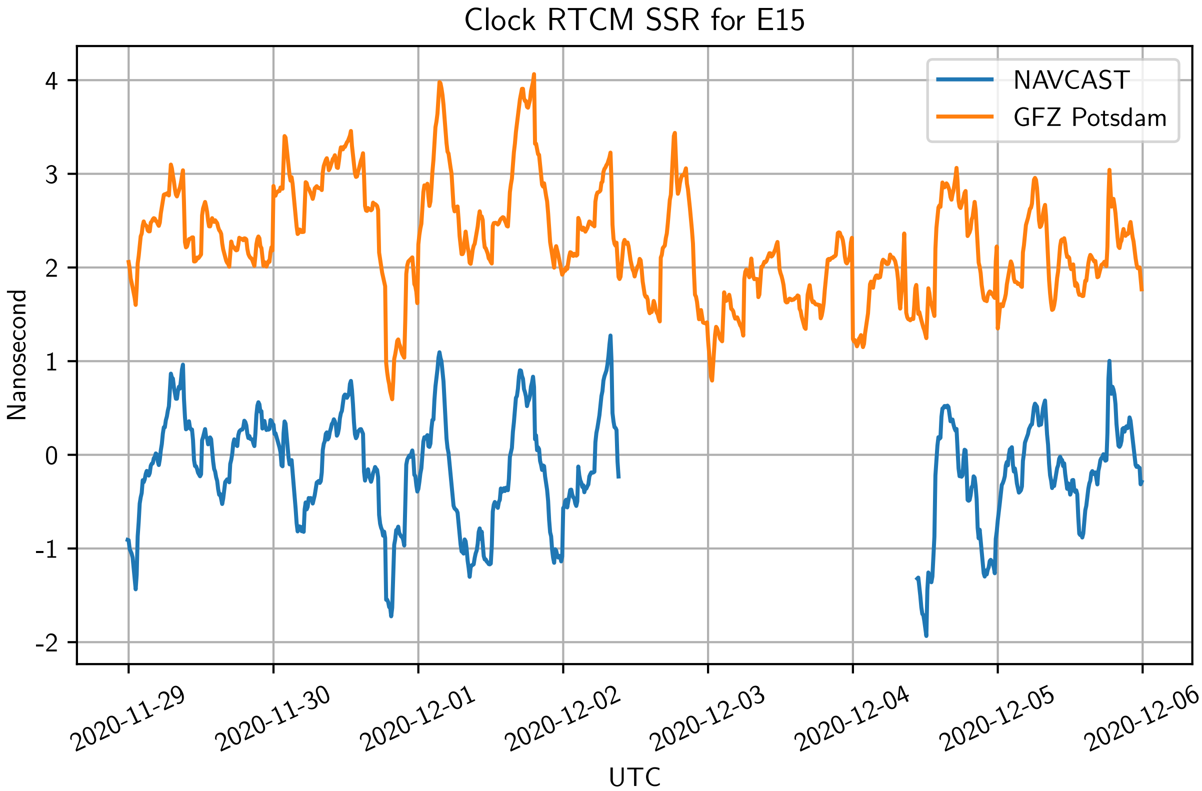


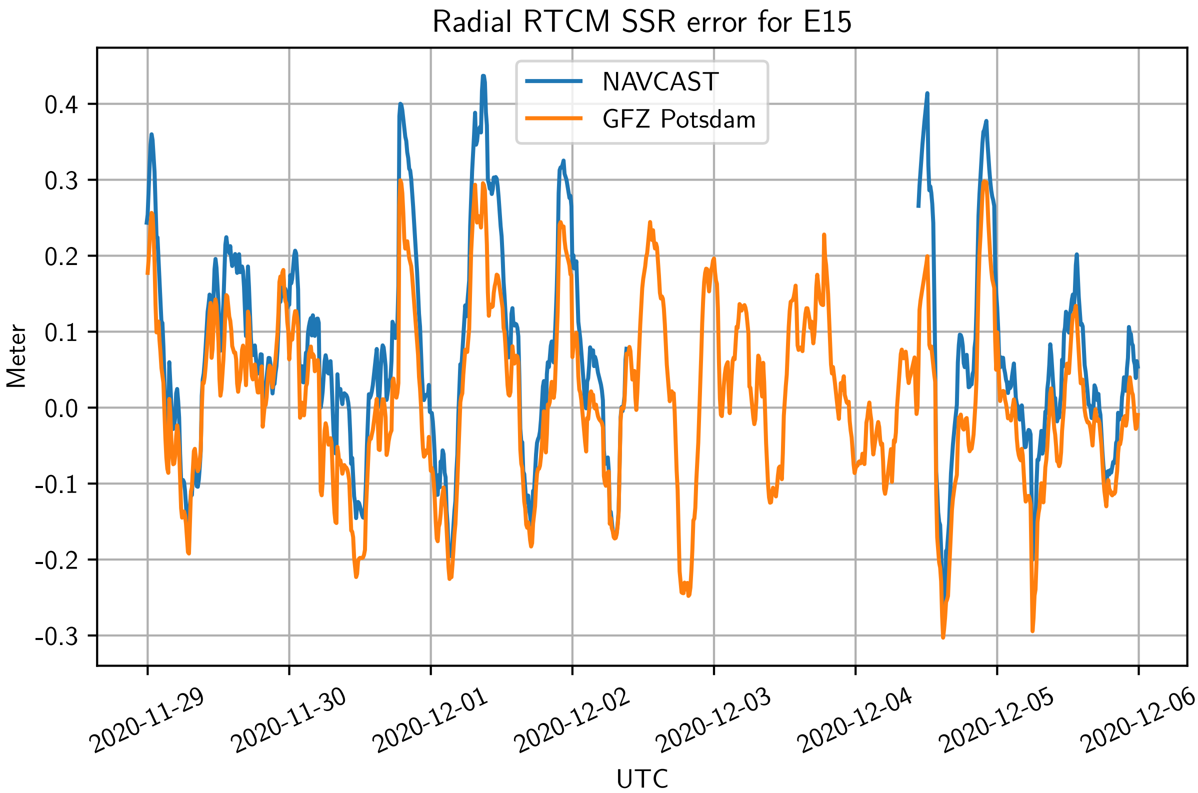
Clock RTCM SSR for E14
NAVCAST
GFZ Potsdam
Nanosecond
5
4
3
2
1
0
-1
-2
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC



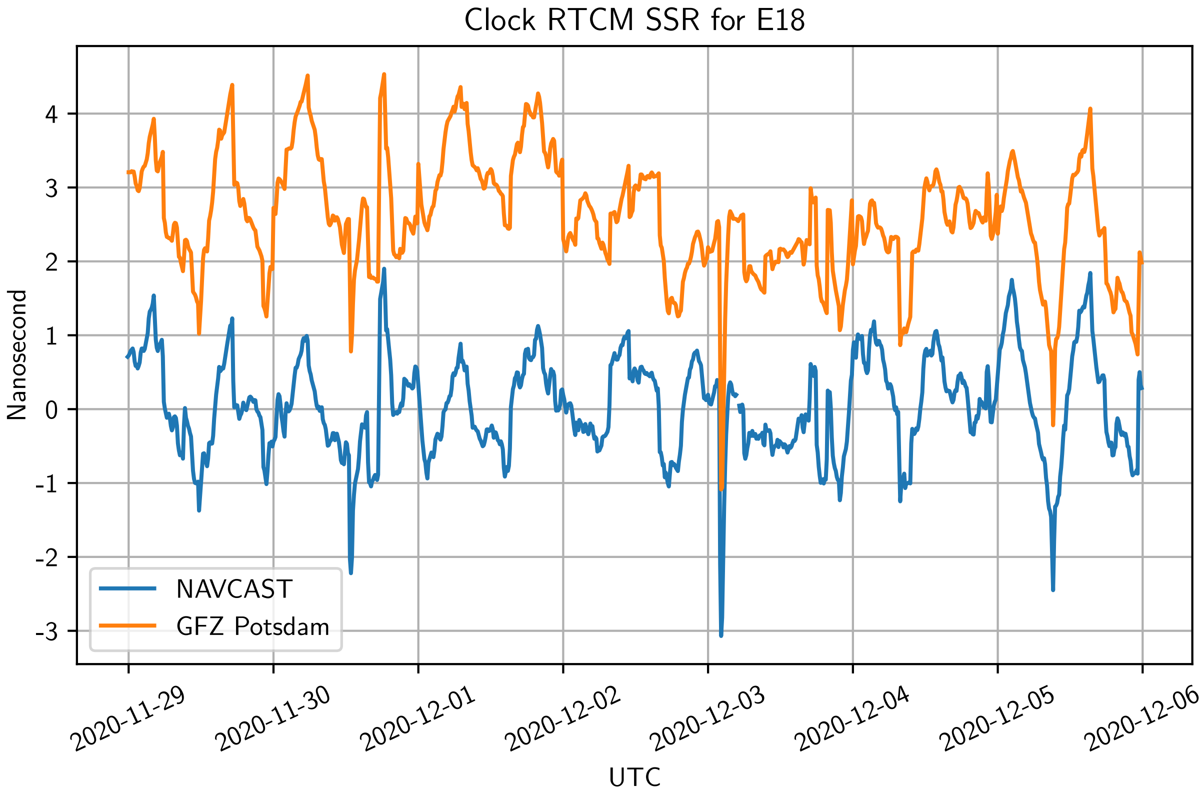
Radial RTCM SSR error for E14
NAVCAST
GFZ Potsdam
Meter
0.4
0.2
0.0
-0.2
-0.4
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E15

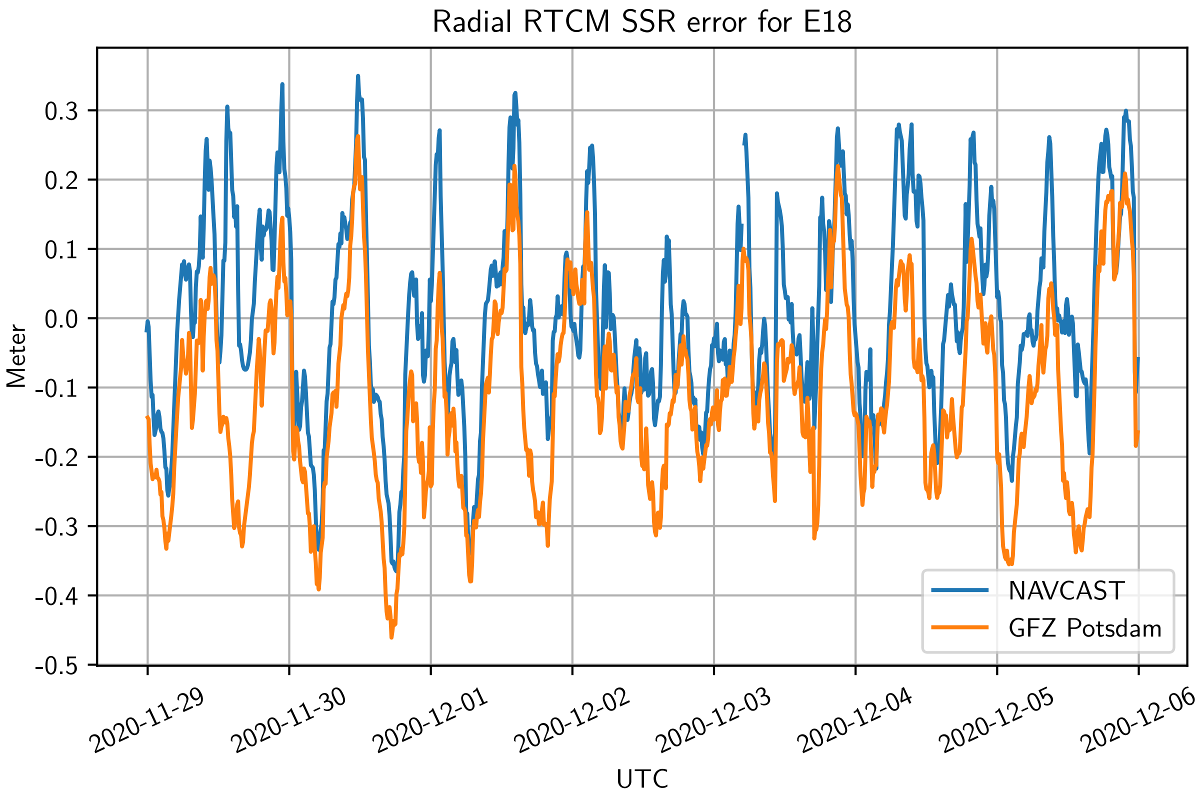

Clock RTCM SSR for E15
NAVCAST
GFZ Potsdam
Nanosecond
4
3
2
1
0
-1
-2
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC


Radial RTCM SSR error for E15
NAVCAST
GFZ Potsdam
Meter
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E18

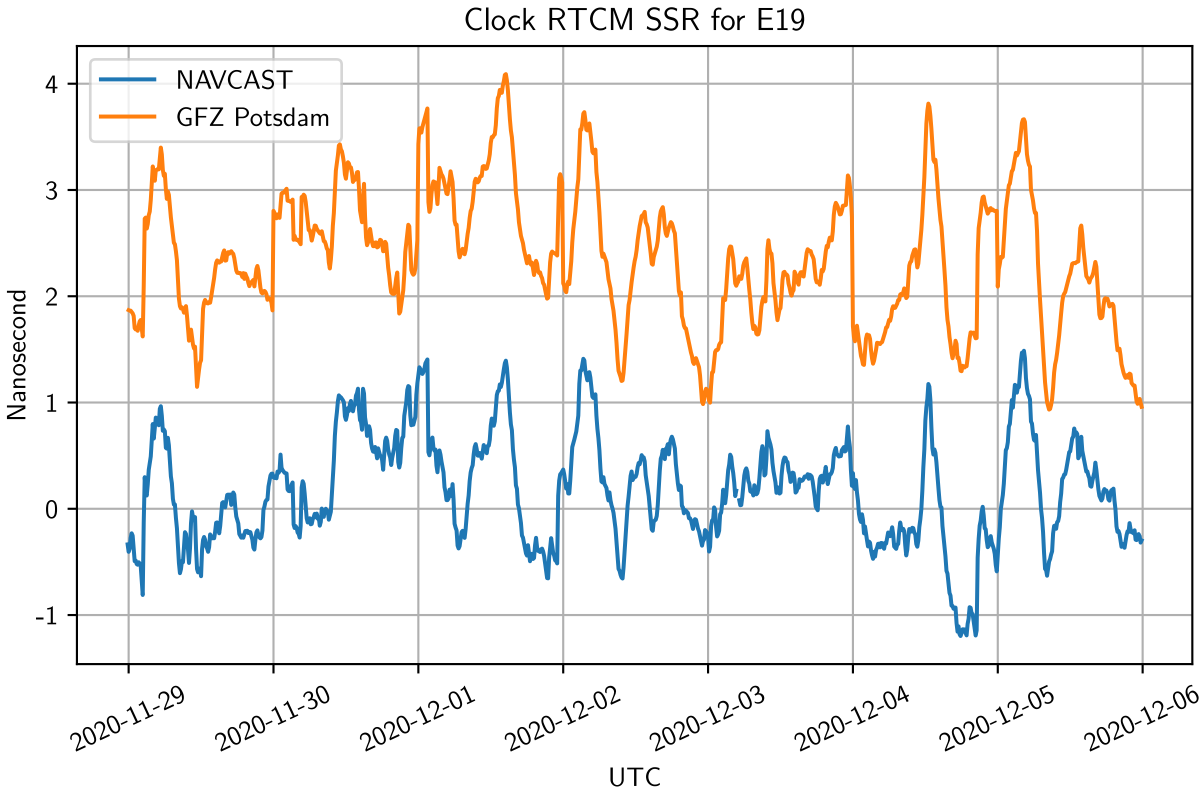


Clock RTCM SSR for E18
Nanosecond
4
3
2
1
0
-1
-2
-3
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

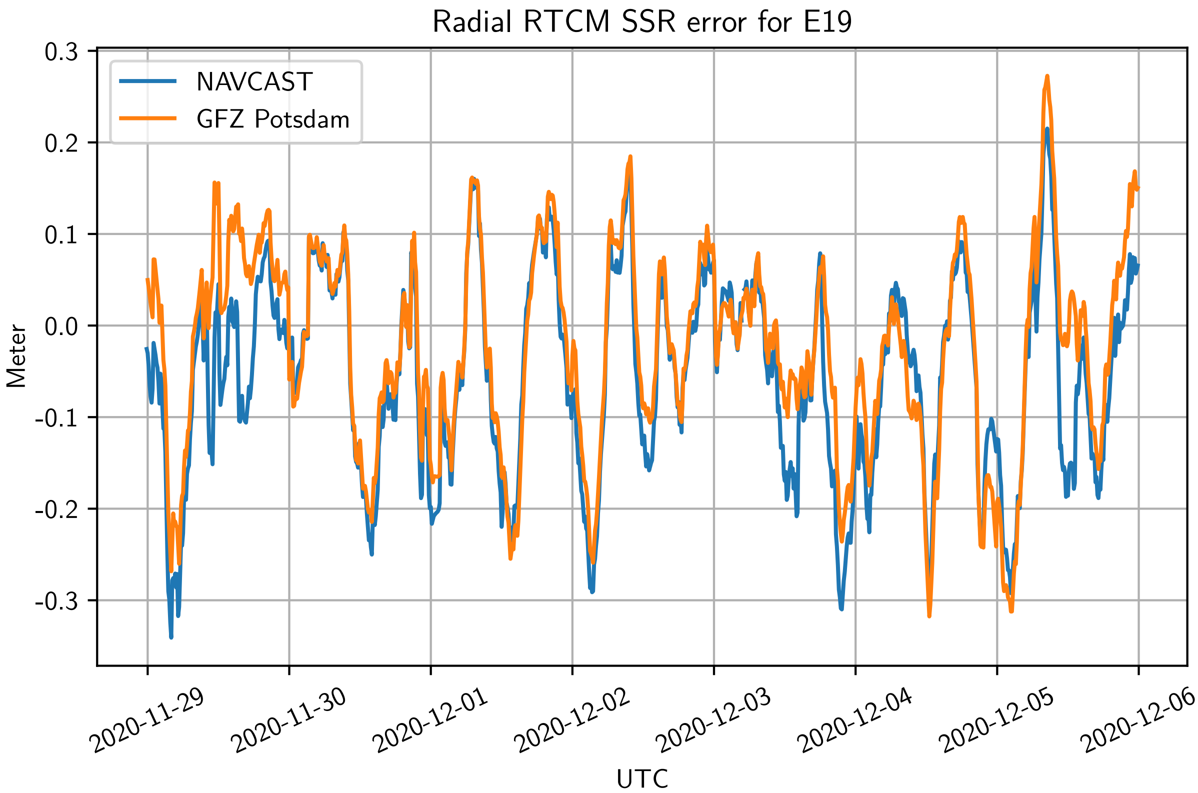


Radial RTCM SSR error for E18
Meter
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E19

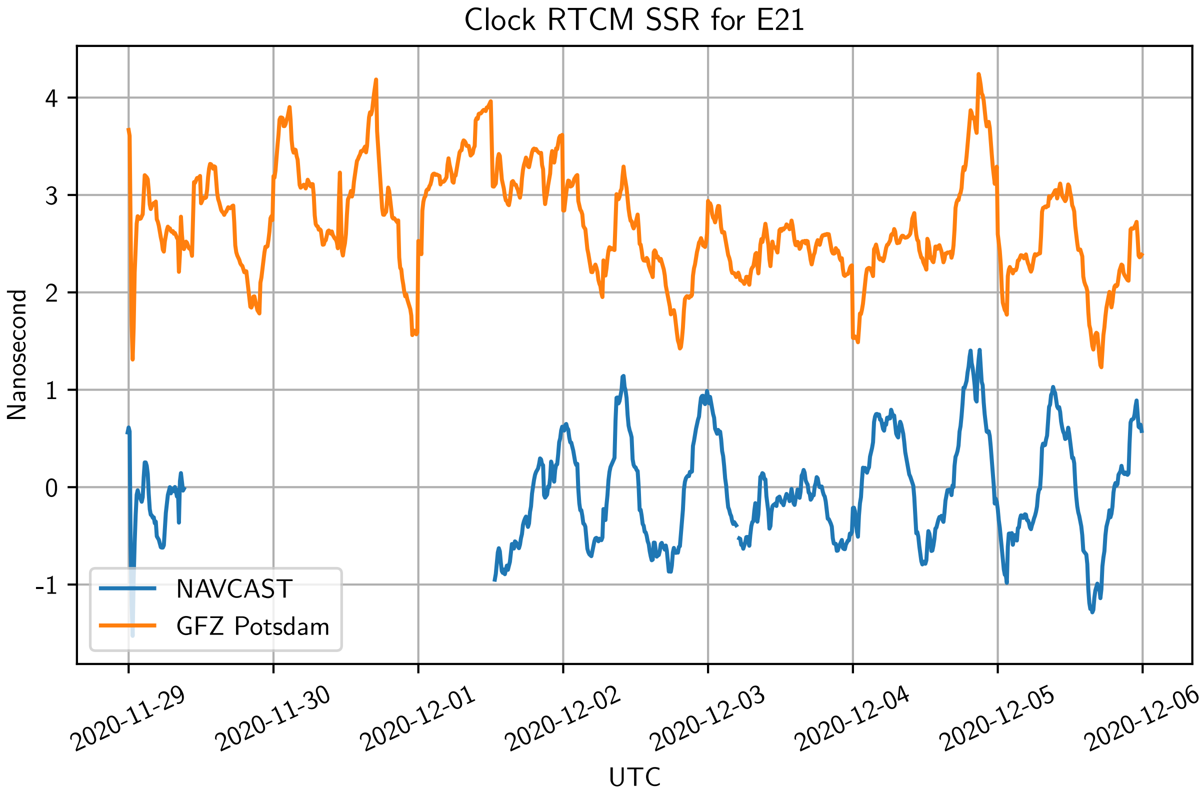


Clock RTCM SSR for E19
NAVCAST
GFZ Potsdam
Nanosecond
4
3
2
1
0
-1
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

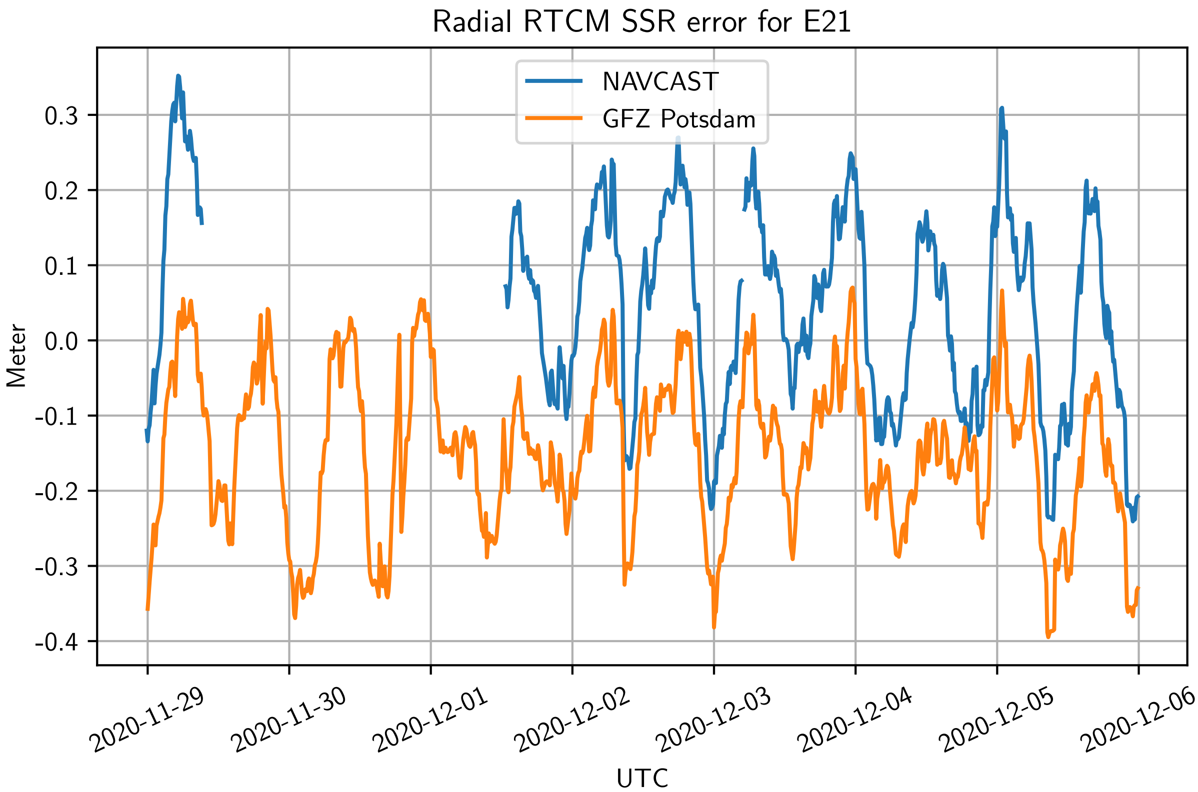


Radial RTCM SSR error for E19
NAVCAST
GFZ Potsdam
Meter
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E21

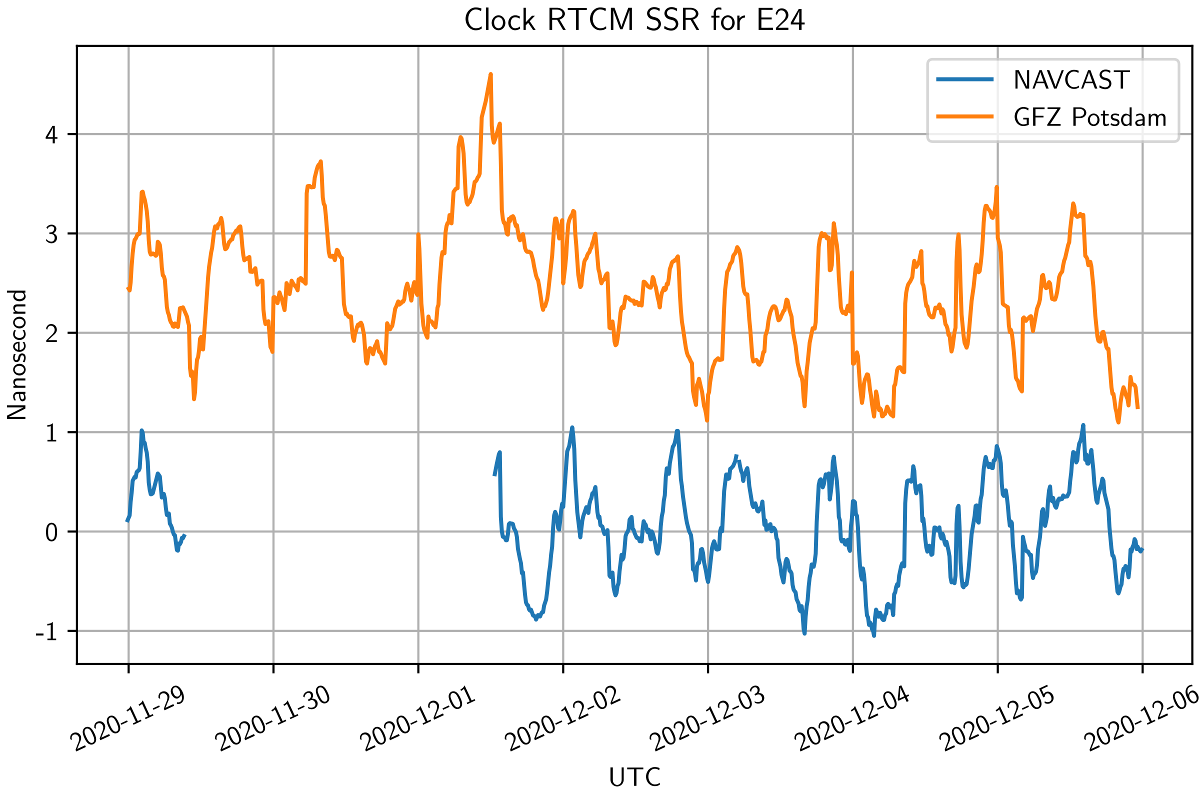


Clock RTCM SSR for E21
Nanosecond
4
3
2
1
0
-1
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

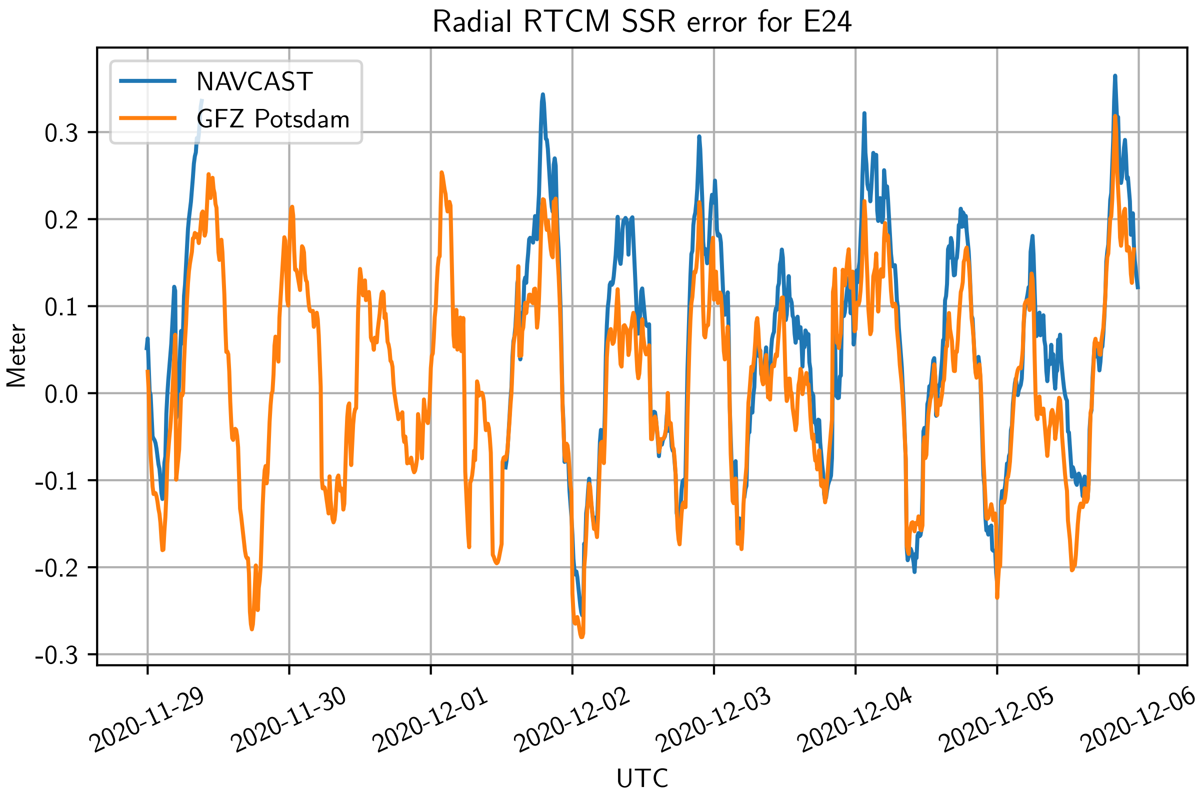


Radial RTCM SSR error for E21
Meter
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E24

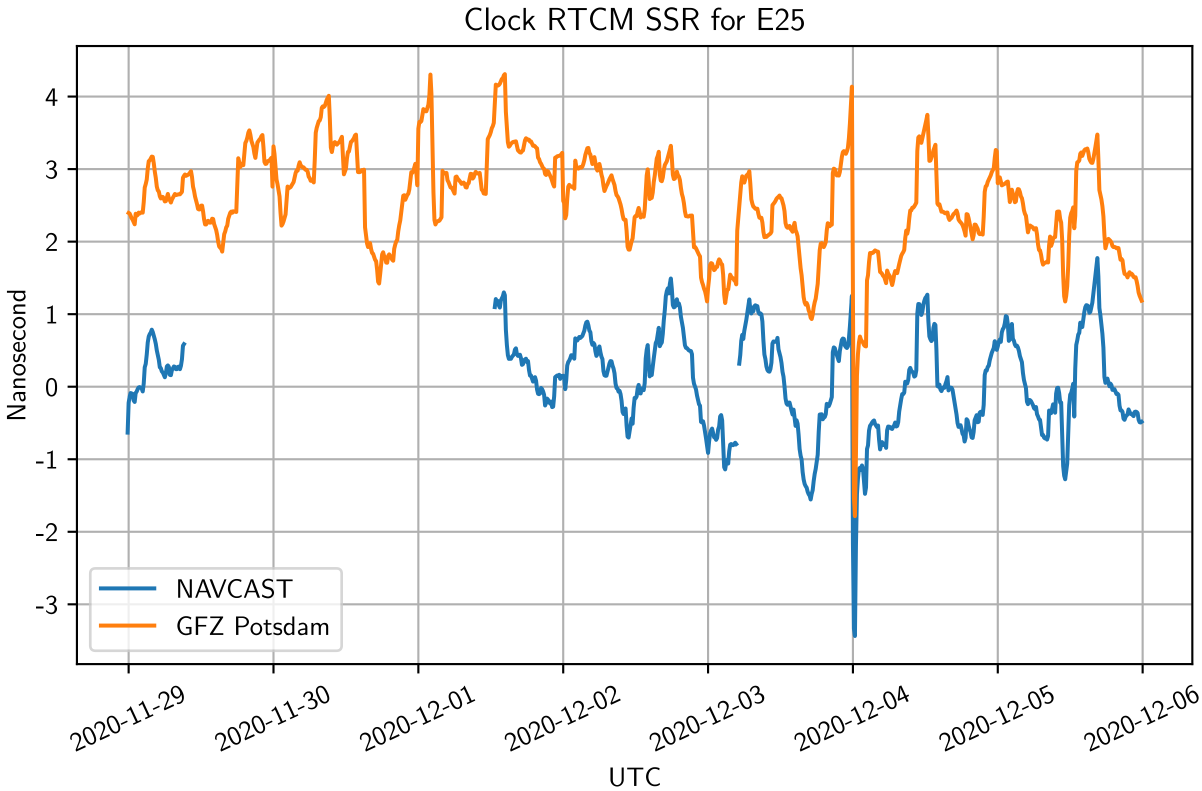


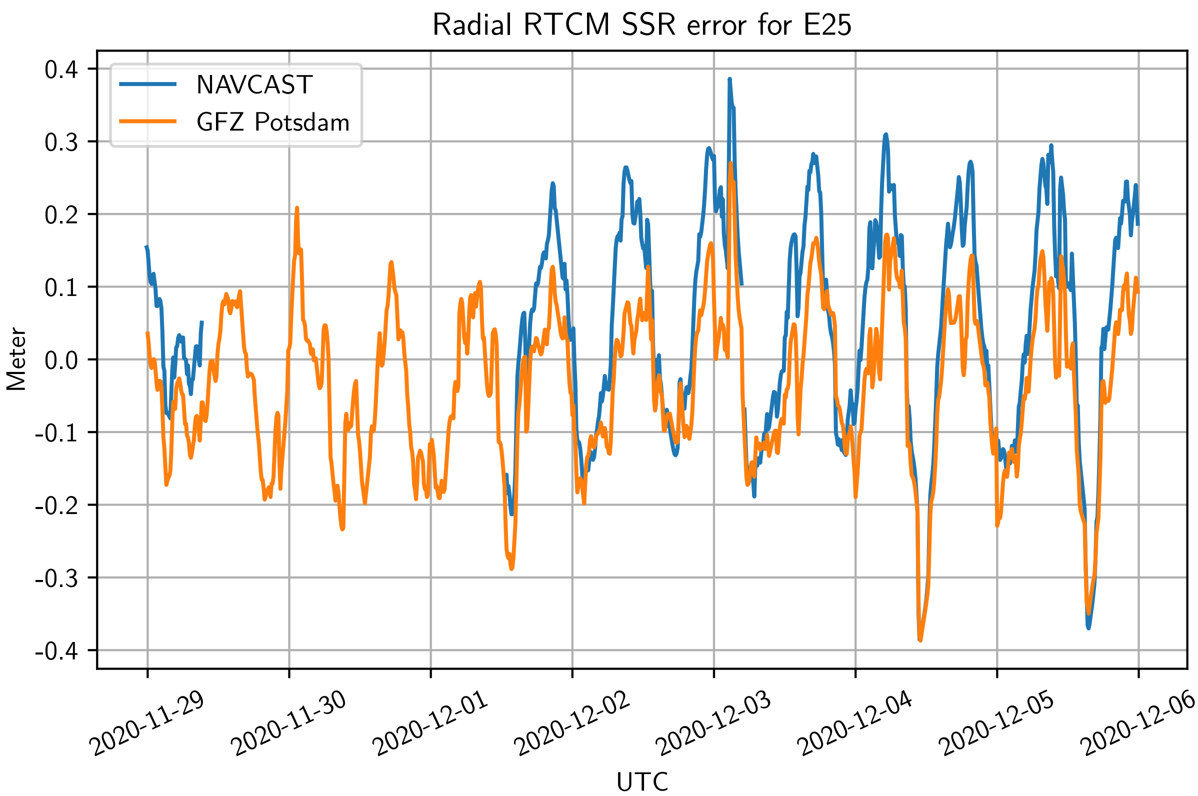
Clock RTCM SSR for E24
NAVCAST
GFZ Potsdam
Nanosecond
4
3
2
1
0
-1
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC



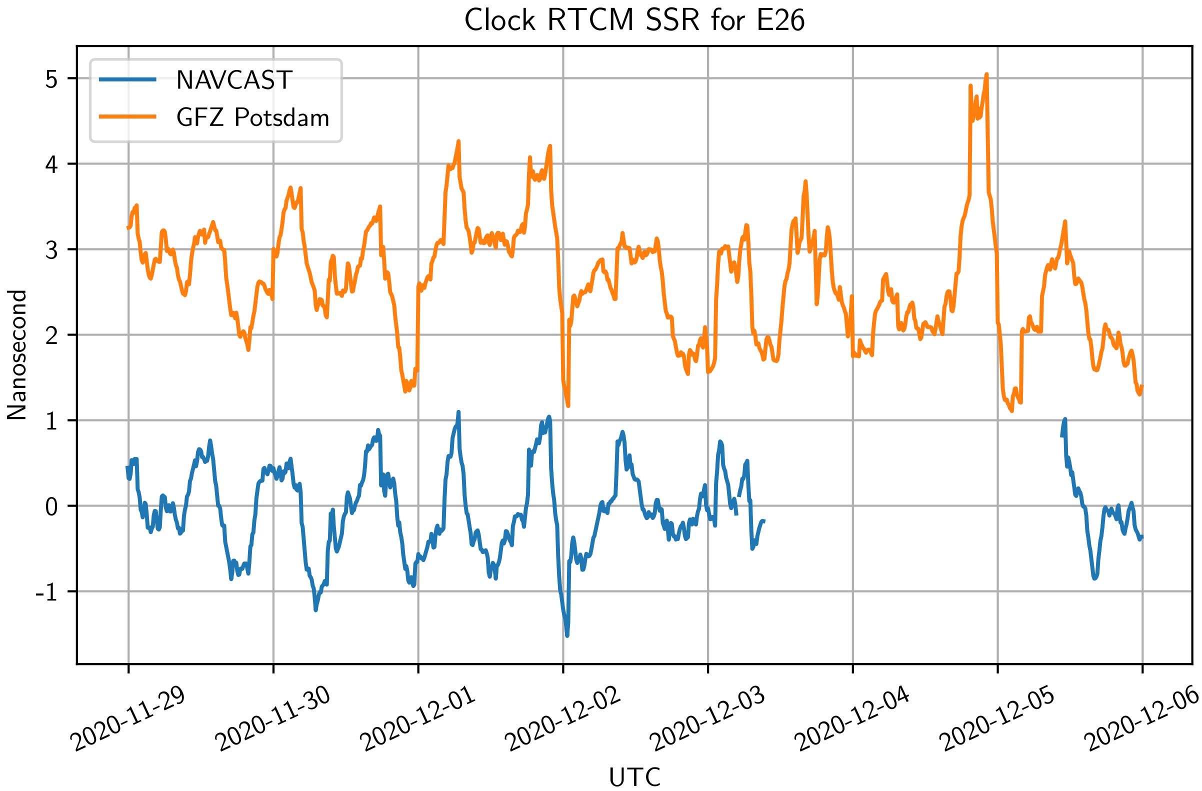
Radial RTCM SSR error for E24
NAVCAST
GFZ Potsdam
Meter
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E25

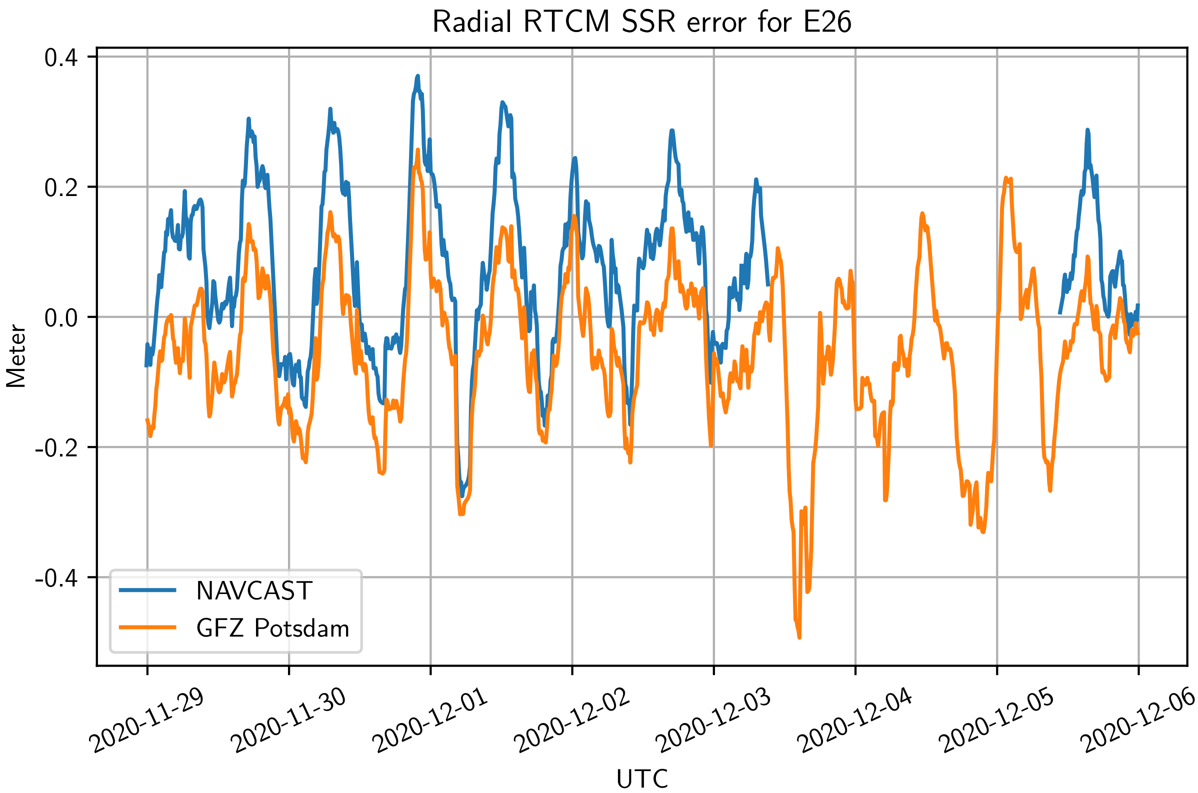

Clock RTCM SSR for E25
Nanosecond
4
3
2
1
0
-1
-2
-3
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC


Radial RTCM SSR error for E25
Meter
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E26

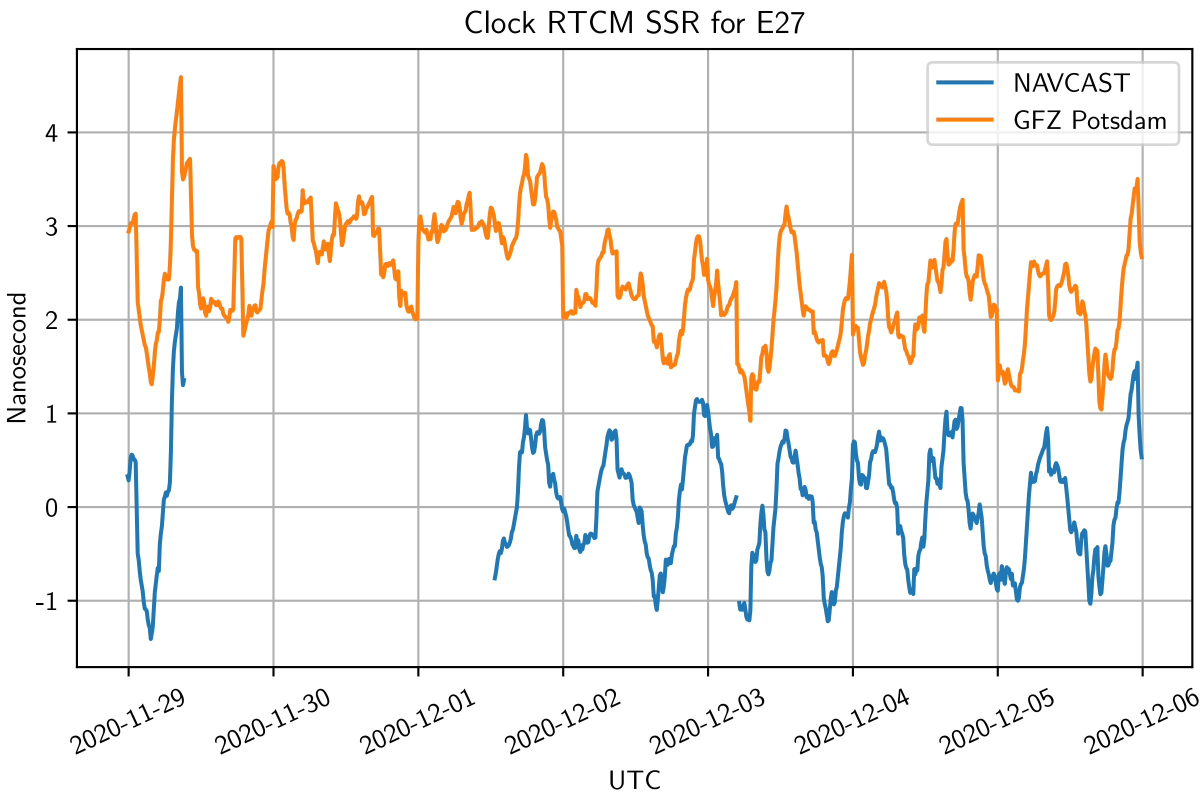


Clock RTCM SSR for E26
NAVCAST
GFZ Potsdam
Nanosecond
UTC
5
4
3
2
1
0
-1
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06

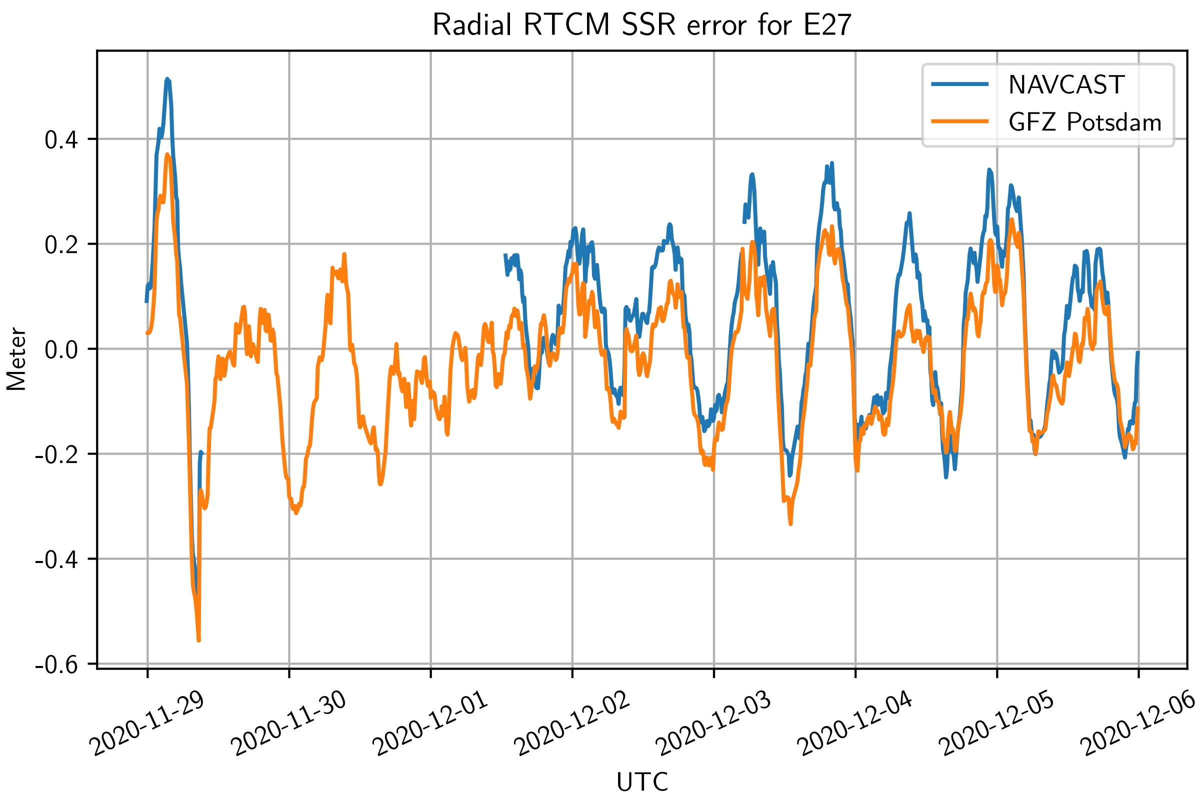


Radial RTCM SSR error for E26
NAVCAST
GFZ Potsdam
Meter
UTC
0.4
0.2
0.0
-0.2
-0.4
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06

E27

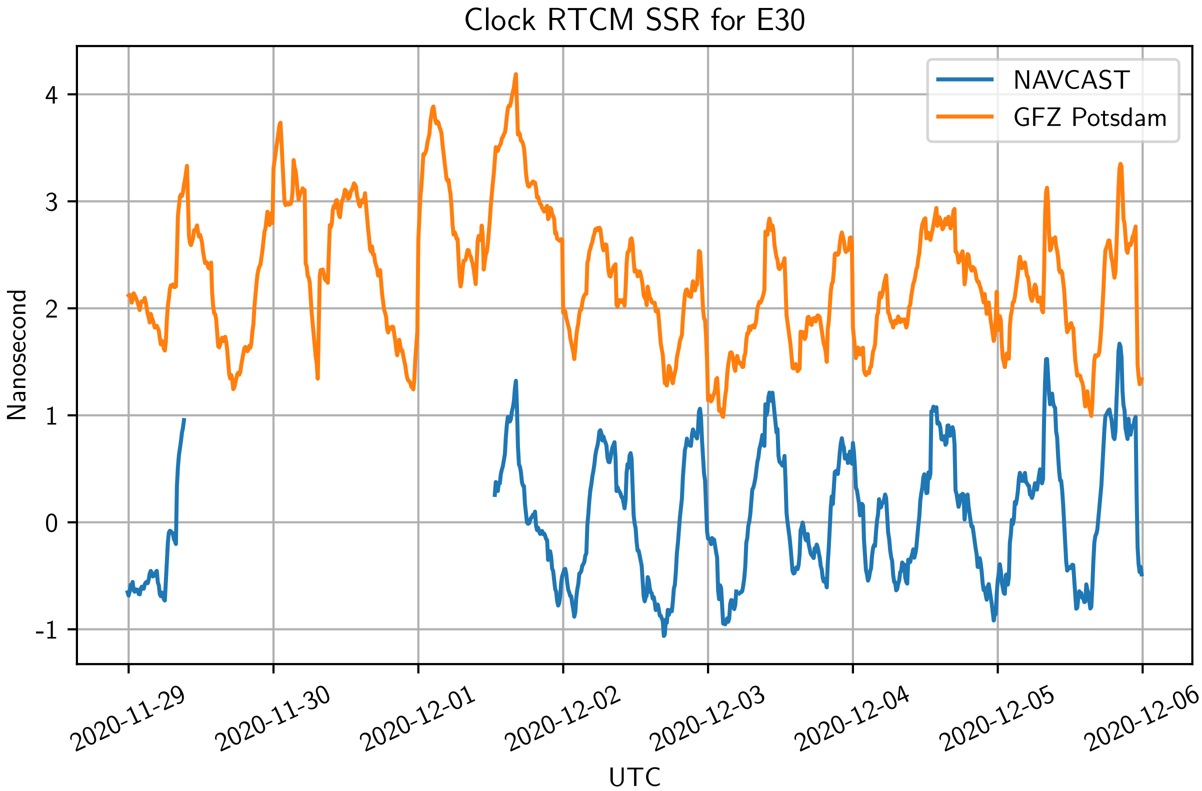


Clock RTCM SSR for E27
NAVCAST
GFZ Potsdam
Nanosecond
4
3
2
1
0
-1
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

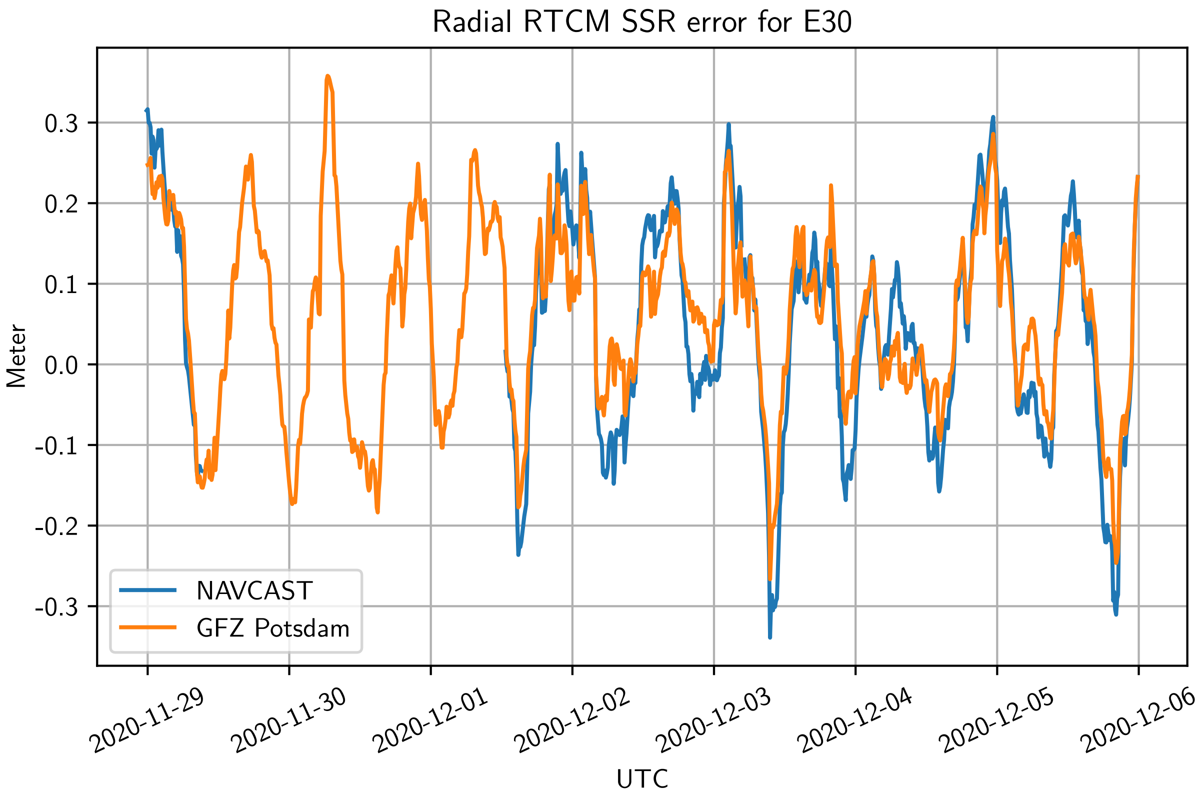


Radial RTCM SSR error for E27
NAVCAST
GFZ Potsdam
Meter
0.4
0.2
0.0
-0.2
-0.4
-0.6
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E30

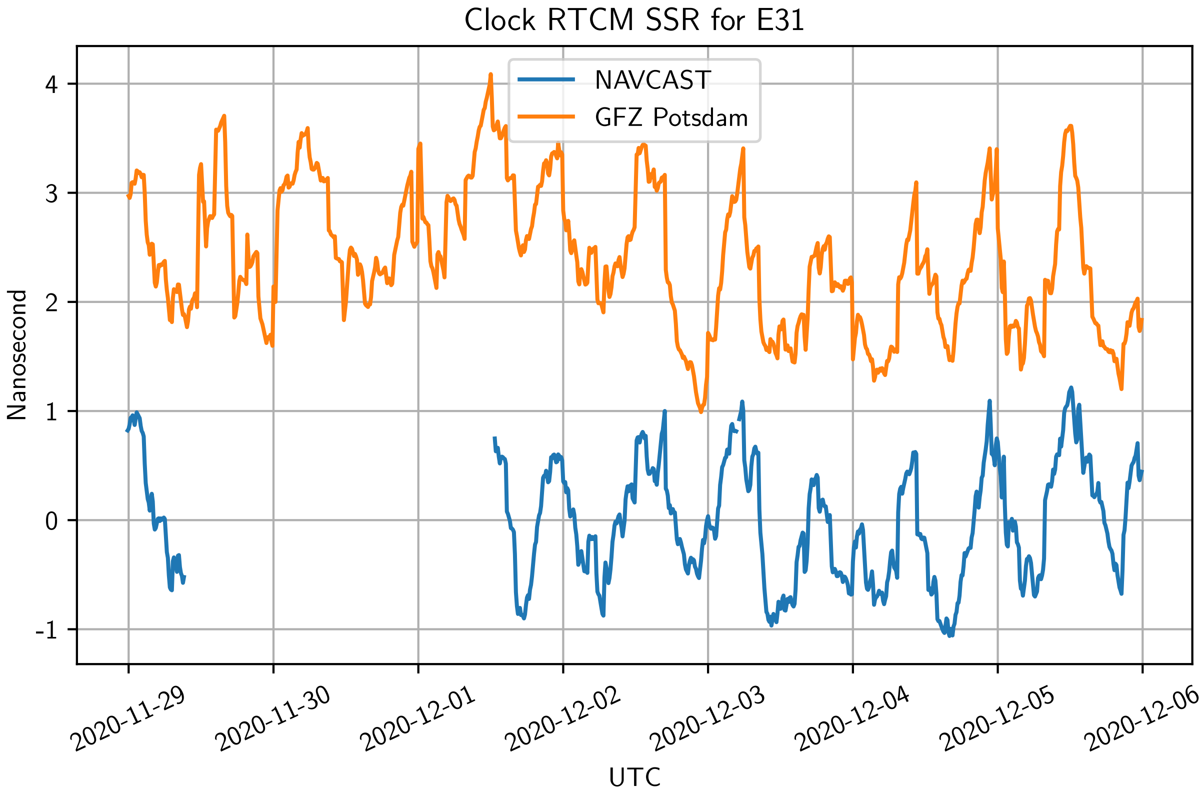


Clock RTCM SSR for E30
NAVCAST
GFZ Potsdam
Nanosecond
4
3
2
1
0
-1
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

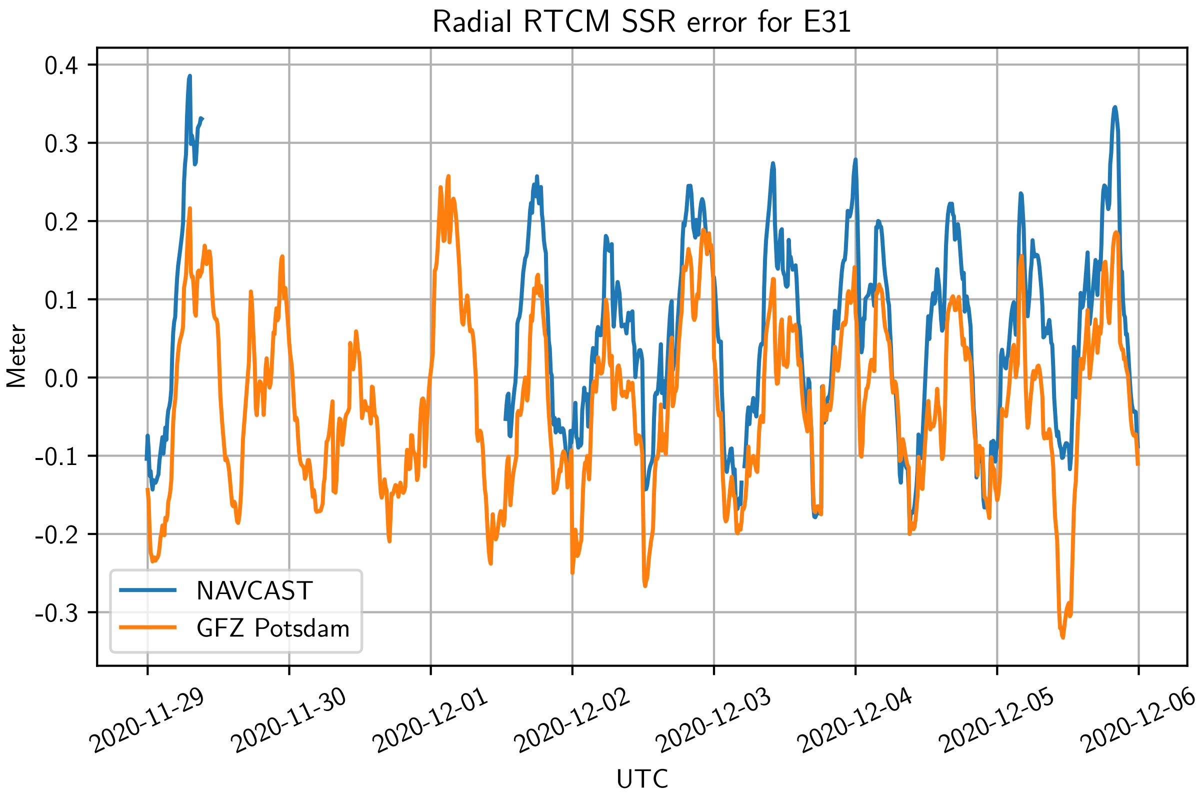


Radial RTCM SSR error for E30
Meter
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E31

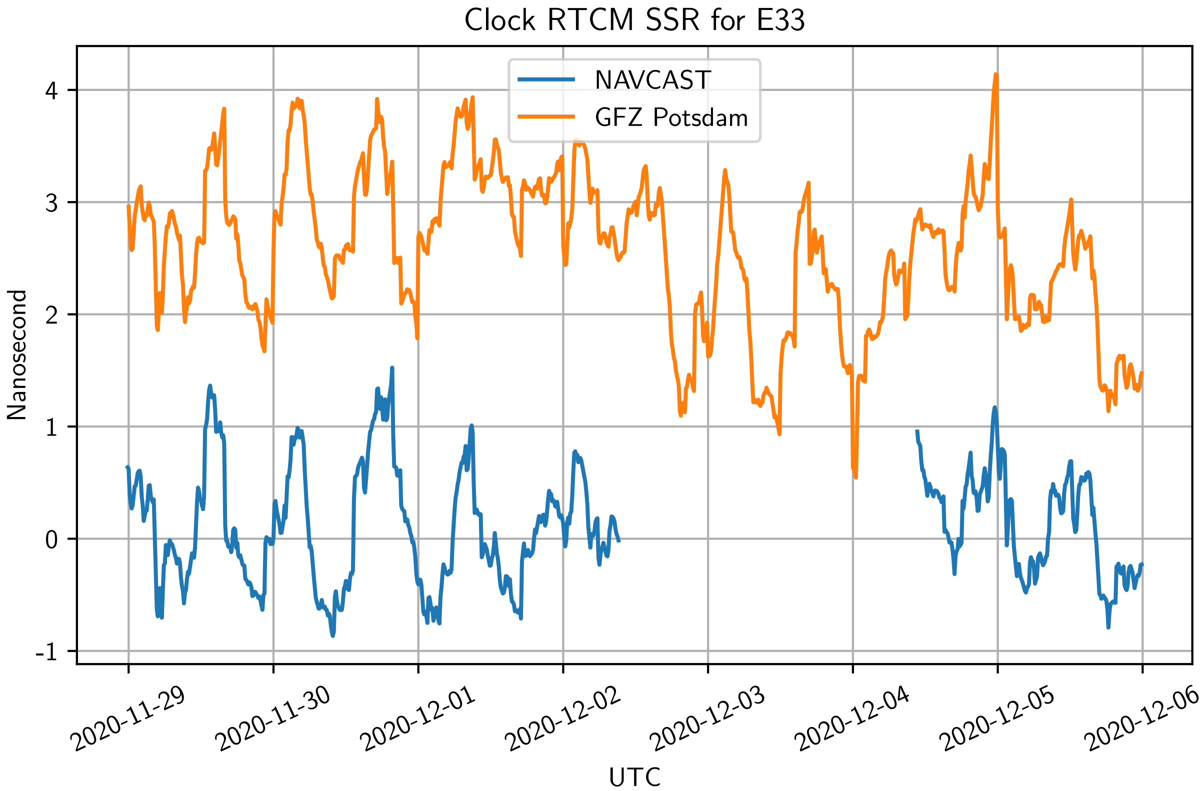


Clock RTCM SSR for E31
NAVCAST
GFZ Potsdam
Nanosecond
4
3
2
1
0
-1
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

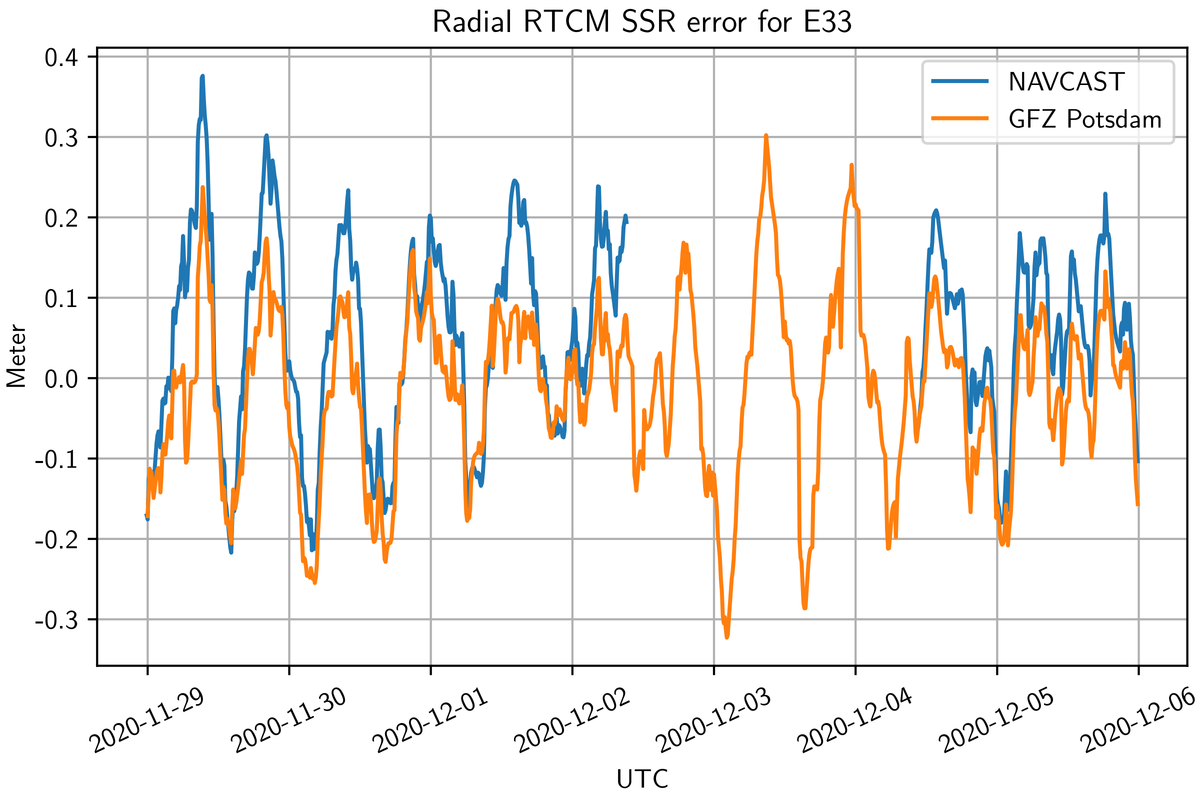


Radial RTCM SSR error for E31
Meter
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
NAVCAST
GFZ Potsdam
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E33

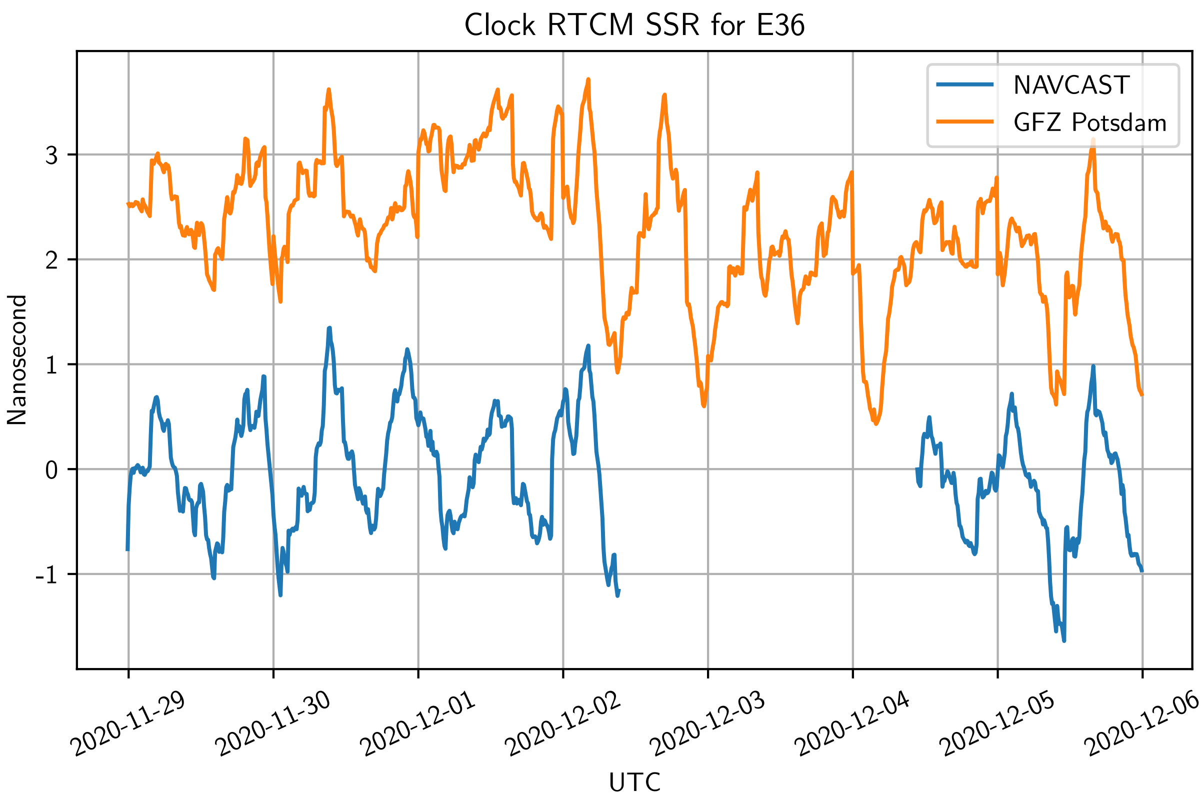


Clock RTCM SSR for E33
NAVCAST
GFZ Potsdam
Nanosecond
4
3
2
1
0
-1
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

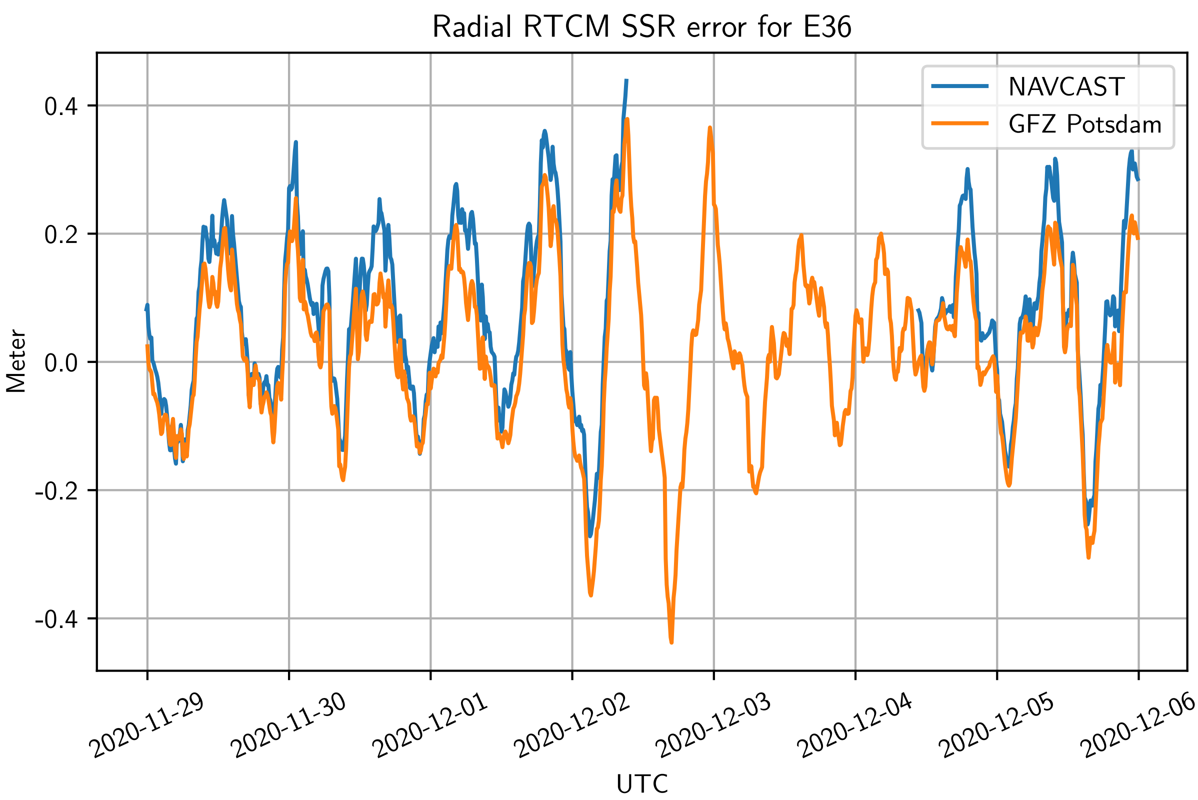


Radial RTCM SSR error for E33
NAVCAST
GFZ Potsdam
Meter
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC

E36



Clock RTCM SSR for E36
NAVCAST
GFZ Potsdam
Nanosecond
3
2
1
0
-1
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC



Radial RTCM SSR error for E36
NAVCAST
GFZ Potsdam
Meter
0.4
0.2
0.0
-0.2
-0.4
2020-11-29
2020-11-30
2020-12-01
2020-12-02
2020-12-03
2020-12-04
2020-12-05
2020-12-06
UTC