Grid Frequency Analysis

Michael Glavind Bülow Pedersen

Research Objectives

1. Download data from an API and a Web server.
2. Store and handle a large dataset ($31,536,001$ observations per year).
3. Handle timeseries data that cross daylight saving.
4. Create beautiful, informative graphs using both ggplot2 and lattice.
5. Craft a piece of reproducable research.
6. Answer research questions:
   - What differences in grid frequency quality can be observed between the Nordic and Continental electricity grids?
   - Is the European power grid frequency exactly 50 Hz on average?

Introduction

The European electricity grid consists of several distinct frequency areas. One frequency area is the Nordic grid which covers Norway, Finland, Sweden and Eastern Denmark. Another frequency area is the Continental grid which covers countries such as Germany, France, Spain, Portugal, Italy, Slovenia, Czech Republic, Switzerland, Slovkia, Poland, and all the way to the border of Turkey…

To keep a power grid stable, it is necessary for the grid frequency to move within a narrow band around a predetermined value. For the European grid the setpoint has been fixed at a reference frequency of 50 Hz+-1mHz. Whenever the frequency moves below this level, Transmission System Operators have contracted grid connected market participants to supply power to the grid at seconds notice. Similarly, if the frequency moves above 50 Hz TSO's have contracted participants to withdraw power from the grid.

In the Continental grid extreme events are characterized by frequencies +- 100 mHz. Especially the low frequencies bound is critical because below -100 mHz all primary reserves have been exhausted and the grid has to cope with additional loss off generation. Below -150 mHz there is a real risk of power plants dropping out, because of the low frequency. On the other end, at +200 mHz solar panels are at risk of dropping out to protect their electronics.

In Europe it has also been agreed to run the power system at exactly 50 Hz on average, so that systems can keep track of the approximate time by continuously measuring the frequency. This way the systems know that 50 fluctuations in the grid equal 1 second in realworld time.

But, because accumulated frequency deviations can move the average above 50 Hz on one day it is sometimes necessary to correct the grid frequency by setting a lower reference frequency point on subsequent days. In practice this is done by fixing the frequency setpoint at 49.99 Hz for 24 hours if the grid time is ahead of clock time and at 50.01 Hz if the grid time is behind clock time. When this correction is performed, the correction equals 17.28 seconds/day.

The time correction should be observable in frequency measurements, as a frequency correction in the daily average frequency measurement, whenever the grid time deviates significantly from clock time. We should also observe that the long-run average deviation from 50Hz is zero.

Getting the data

This sections gets nitty gritty on how to retrieve frequency data. For the Continental grid it is straighforward, because the French Transmission System Operator (TSO) RTE provides this data in nicely formatted csv-files. For the Nordic grid however, we have to retrieve the data from an undocumented api at the Norwegian TSO Statnett. This requires some probing and error correction in the code.

If data sources and data retrieval is not of interest, you may proceed to the actual analysis. We end up with two dataset for the first nine months of 2015.

For the Continental grid we have an observation for each 10 seconds leading to $2,099,160$ observations. For the Nordic grid we have an observation each second leading to $20,991,600$ observations.

In the sample period there was a summer Daylight Savings Time (DST) change in Hour 3 on 2015-03-29 where the hour does not exist in local time. Similarly there will be a winter DST change in Hour 3 on 2015-10-25 (not included in sample) where there will be two Hour 3's.

Nordic

We query the API of the Norwegian TSO Statnett to get 1 second measurements ($31,536,000$ observations per year).

The call to the API is http://driftsdata.statnett.no/restapi/Frequency/BySecond?FromInTicks=FromTimeInMs&ToInTicks=ToTimeInMs. This GET request returns 1 second measurements as well as startDate and EndDate of the request in Local timezone. The inputs are in ms since epoch and therefore UTC.

Data retrieval is somewhat complicated by the fact that the return data do not have datetimes associated with each observation. This becomes a problem because there are missing observations, which are just excluded from the returned list. This happens for instance on 2015-01-07 15:33:00 to 15:34:00, where only 39 observations are returned. To get a complete dataset we are therefore forced to download an hour, check if it is complete. If not, get each minute and check if complete. If not, get each second and check if complete and if not record NA. This process is time consuming (one GET request for one hour takes appr. 0.3-0.5 sec.), especially when we have to loop across each minute and second. To get a full year the approximate runtime is on the order of multiple hours.

The current implementation sometimes result in duplicate observations being added to the data frame. I have not figured out where duplication occurs, so for now duplicate values are just excluded afterwards using the unique() function.

The API can only return 1 hour of data (probably 3600 observations). So,

```
fromDate <- ymd_hms("2015-10-19 07:00:00")
toDate <- ymd_hms("2015-10-19 08:00:00")
```

returns data from "2015-10-19 09:00:00" to "2015-10-19 09:59:59"

API Examples

The following examples illustrate how Daylight Savings Time (DST) affects return values.

Before DST:

```
fromDate <- dmy_hms("28-03-2015 12:00:00")
toDate <- dmy_hms("28-03-2015 13:00:00")
```

> "2015-03-28 13:00:00"
> "2015-03-28 13:59:59"

After DST:

```
fromDate <- dmy_hms("29-03-2015 12:00:00")
toDate <- dmy_hms("29-03-2015 13:00:00")
```

> "2015-03-29 14:00:00"
> "2015-03-29 14:59:59"

Under DST (02:00-03:00 local time / 01:00-02:00 UTC does not exist):

```
fromDate <- dmy_hms("29-03-2015 00:00:00")
toDate <- dmy_hms("29-03-2015 01:00:00")
```

> "2015-03-29 01:00:00"
> "2015-03-29 01:59:59"

```r
fromDate <- dmy_hms("29-03-2015 00:30:00")
toDate <- dmy_hms("29-03-2015 01:30:00")
```

"2015-03-29 01:30:00"
"2015-03-29 03:29:59"

```r
fromDate <- dmy_hms("29-03-2015 01:00:00")
toDate <- dmy_hms("29-03-2015 02:00:00")
```

"2015-03-29 03:00:00"
"2015-03-29 03:59:59"

Continental

We can query the Website of the French TSO RTE to get 10 second measurements ($3,153,600$ observations per year).

The data is returned as a zip file containing one csv file with 10 second measurements for one month. The format of the date is local time (Europe/Paris), with NA for hour 3 (02:00:00-02:59:50) in spring DST.

There are also a number of missing values in this data set.

Analysis

Initial data validation

Firstly, we check the raw data for missing observations.

```
## Continental: missing 8825 observations ( 0.3742 %)
```

```
## Nordic: missing 1413 observations ( 0.0060 %)
```

The relatively high amount of missing observations in the Continental data stems from one whole April day missing.

Secondly, we print a sample of the raw data. Here we see that even though the Nordic data is recorded at each second, changes only occur every 8-10 secs. This might indicate that the actual sampling is done every 8-10 seconds and not every second leading to a loss in precision.

```r
# Continental:
  head(FC,15)
```

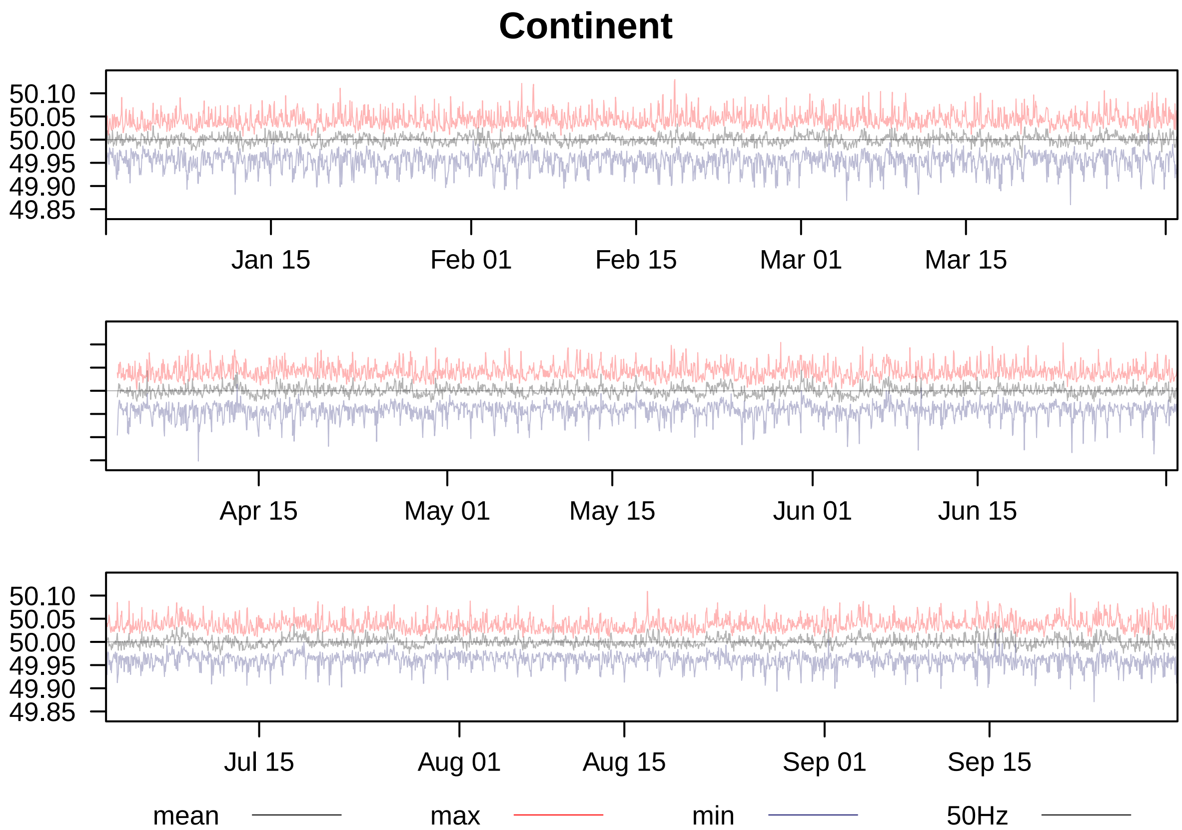
```
##                     frequency
## 2015-01-01 00:00:00   50.0184
## 2015-01-01 00:00:10   50.0169
## 2015-01-01 00:00:20   50.0141
## 2015-01-01 00:00:30   50.0104
## 2015-01-01 00:00:40   50.0025
## 2015-01-01 00:00:50   50.0016
## 2015-01-01 00:01:00   50.0014
## 2015-01-01 00:01:10   50.0092
## 2015-01-01 00:01:20   50.0023
## 2015-01-01 00:01:30   50.0021
## 2015-01-01 00:01:40   50.0009
## 2015-01-01 00:01:50   49.9965
## 2015-01-01 00:02:00   49.9853
## 2015-01-01 00:02:10   49.9796
## 2015-01-01 00:02:20   49.9749
```

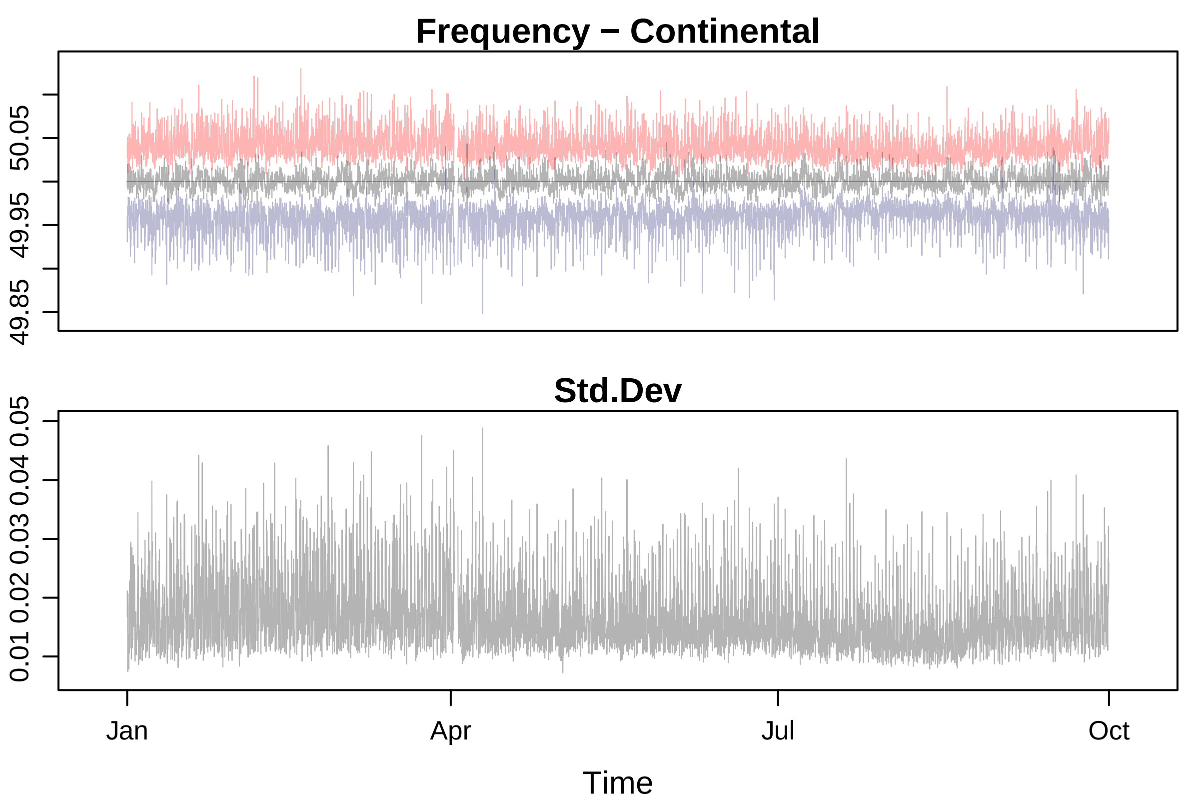
```r
# Nordic:
  head(FN,15)
```

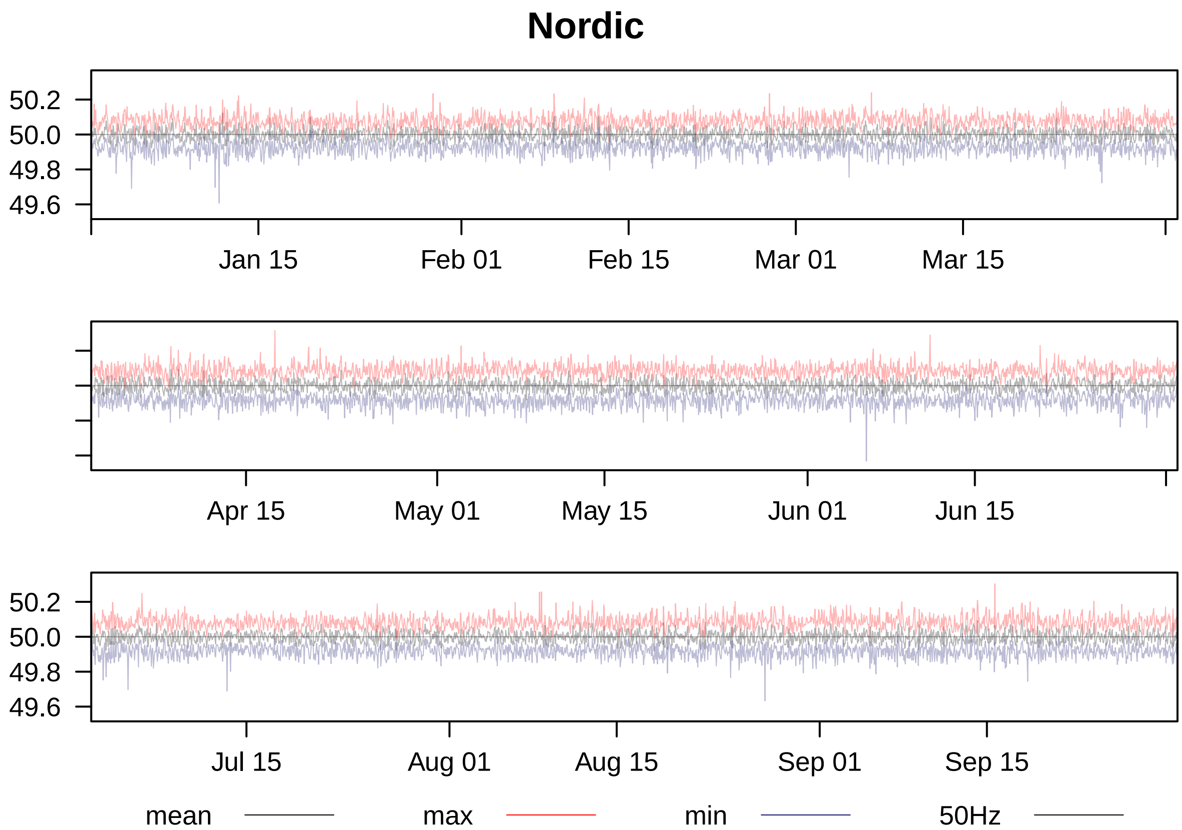
```
##                     frequency
## 2015-01-01 00:00:00    49.994
## 2015-01-01 00:00:01    49.994
## 2015-01-01 00:00:02    49.994
## 2015-01-01 00:00:03    49.994
## 2015-01-01 00:00:04    49.994
## 2015-01-01 00:00:05    49.963
## 2015-01-01 00:00:06    49.963
## 2015-01-01 00:00:07    49.963
## 2015-01-01 00:00:08    49.963
## 2015-01-01 00:00:09    49.963
## 2015-01-01 00:00:10    49.963
## 2015-01-01 00:00:11    49.963
## 2015-01-01 00:00:12    49.963
## 2015-01-01 00:00:13    49.963
## 2015-01-01 00:00:14    49.949
```

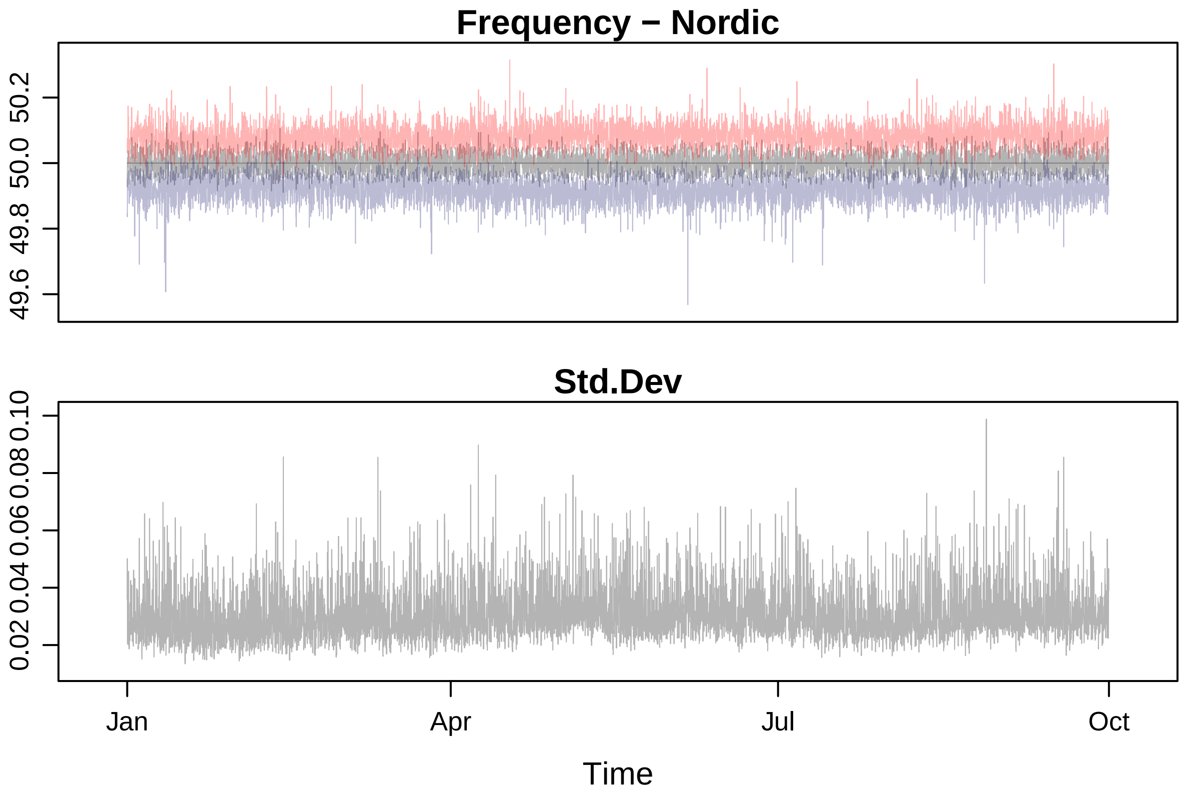
Exploring the data

To get an initial understanding of the data, we plot the average, maximum, and minimum grid frequency for each hour in the test sample. From the two graphs it is evident that the Nordic grid frequency shows significantly more extreme values than the Continental grid and has a larger variation within hours. This might be because of the more frequent grid measurements in the raw Nordic data, but is also the expected result as a smaller grid, such as the Nordic, has less capacity to absord power imbalances and therefore could show larger frequency variations.


Continent
50.10
50.05
50.00
49.95
49.90
49.85
Jan 15
Feb 01
Feb 15
Mar 01
Mar 15
Apr 15
May 01
May 15
Jun 01
Jun 15
Jul 15
Aug 01
Aug 15
Sep 01
Sep 15
mean
max
min
50Hz

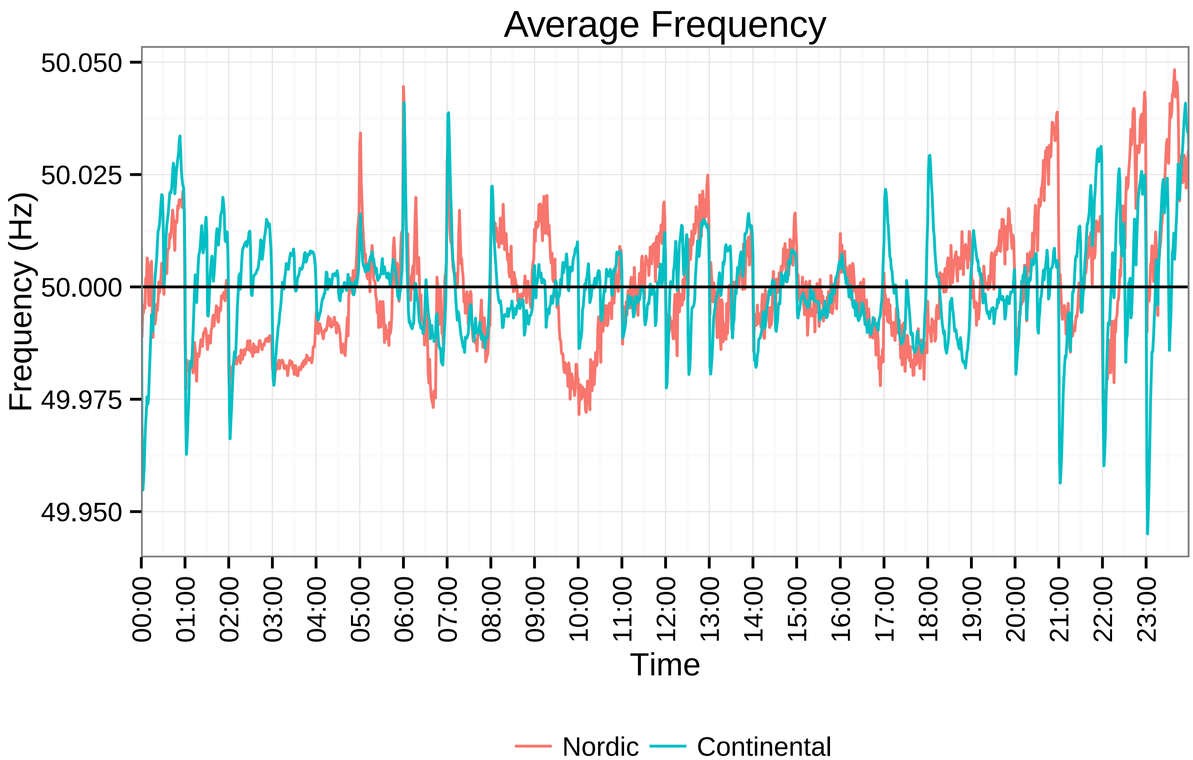

Frequency − Continental
50.05
49.95
49.85
Std.Dev
0.01 0.02 0.03 0.04 0.05
Jan
Apr
Jul
Oct
Time


Nordic
50.2
50.0
49.8
49.6
Jan 15
Feb 01
Feb 15
Mar 01
Mar 15
Apr 15
May 01
May 15
Jun 01
Jun 15
Jul 15
Aug 01
Aug 15
Sep 01
Sep 15
mean
max
min
50Hz



Next, we create a plot of the average grid frequency across the day.
Here we observe clear trends in the grid frequency with notable spikes around the changes in hour. This is likely a market design artifact that materializes because trading and interchange scheduling between countries is typically done in hourly intervals (though during the last 5 years quarterly periods has also begun trading with some volume internally in Germany). So when the power flows change around the hour a mismatch in timing can affect the grid frequency.

The largest variation for the Continent is seen around evening/night when generation has to adapt to a falling consumption and in the morning where consumption pick up and generations has to follow. For the Nordic system, we largely see the same pattern.

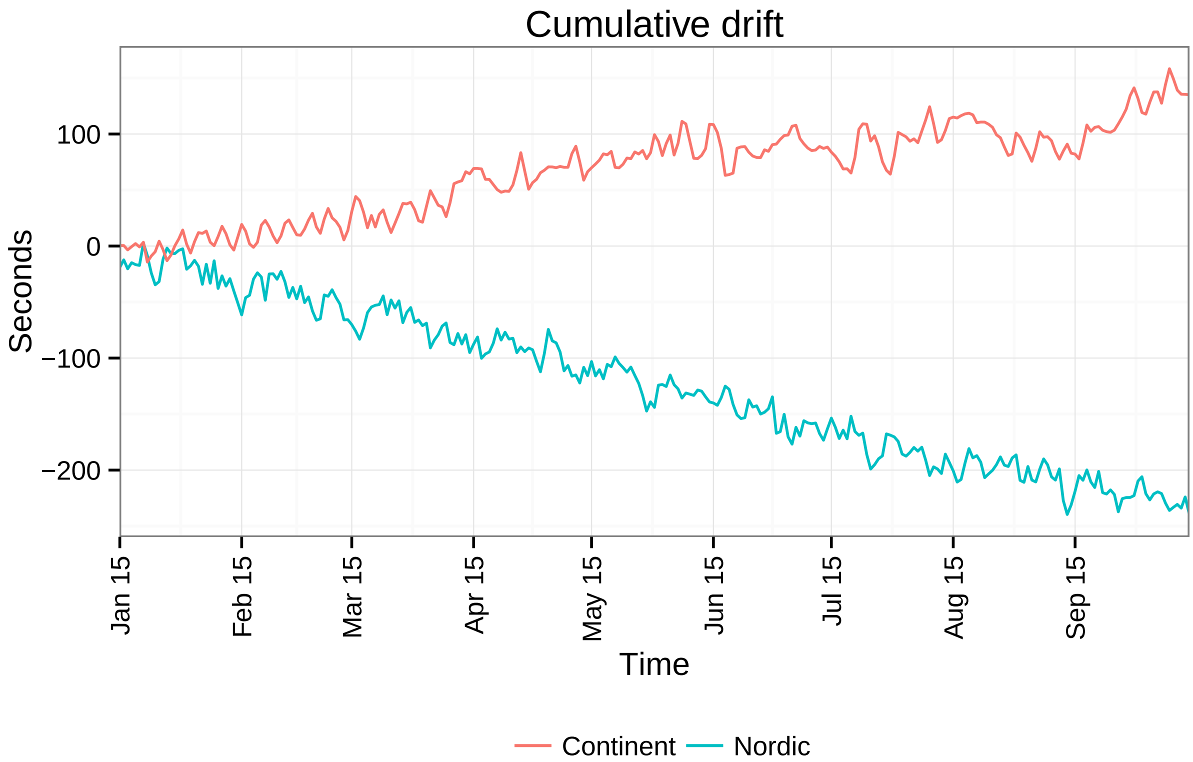


Frequency drift

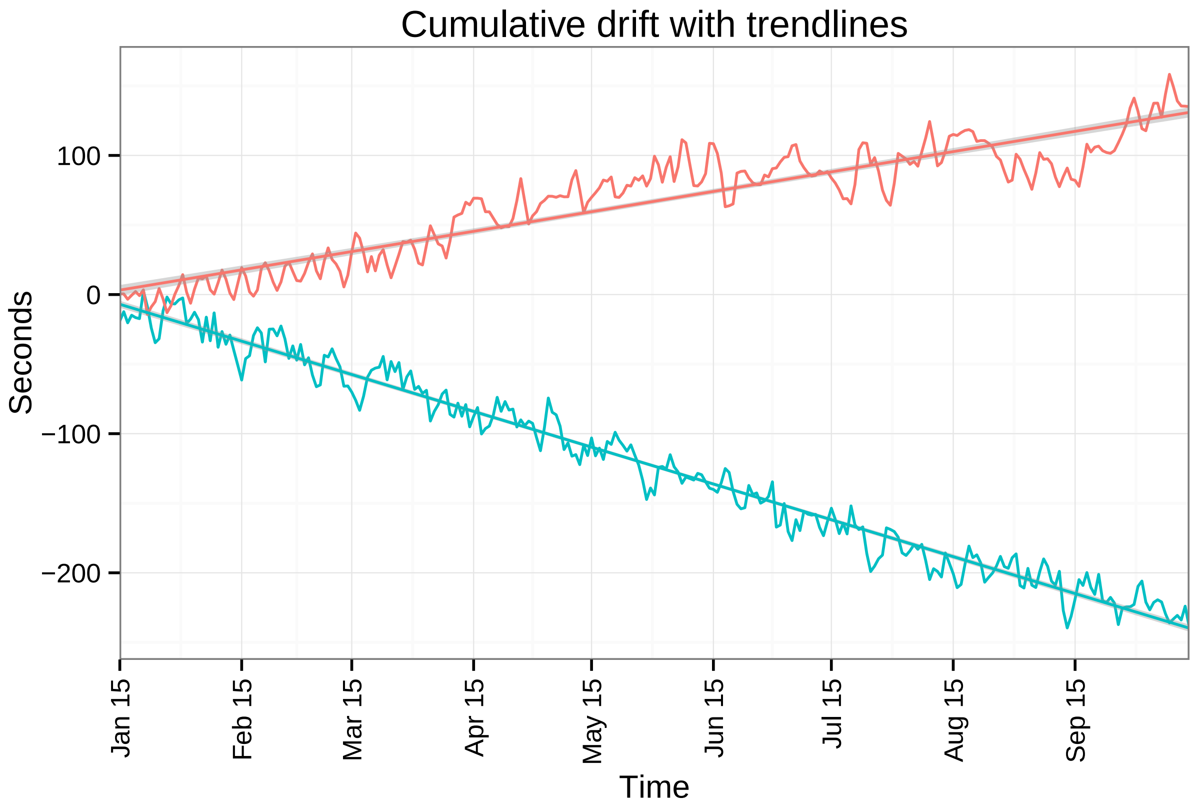
Last, we plot the clock drift in the two grids. This is the amount of seconds that a grid-run clock would deviate from an atomic clock during the period. We see that, contrary to the previous statements, the clock drift is not zero. In the Continental grid the clock would run around 140 seconds faster on 1. Oktober compared to the atomic clock, while the Nordic clock would run around 225 seconds slower.

On the homepage of Swissgrid we can see the current clock drift for the Continental grid (which is nowhere near as much off). This suggests that our data lacks the true precision needed to run an accurate grid clock.
This could either be due to the observations being point measurements of grid frequency (instead of providing the average over the last 1/10 seconds), it could be a small lack of precision in each measurement that adds up, or it could be due to shifts during the periods with missing data (the frequency during missing periods is assumed to be 50Hz exactly so there is no change in clock drift).

Nonetheless, we do see clear reversals in the grid frequency. Fitting a straight line to the data points (to account for a constant drift in the series) we observe what looks like a reversal to this trend line.



Cumulative drift
Seconds
100
0
−100
−200
Jan 15
Feb 15
Mar 15
Apr 15
May 15
Jun 15
Jul 15
Aug 15
Sep 15
Time
Continent
Nordic



Conclusion

In this short project, we have shown how to download frequency measurements at a 1/10 second resolution from the webpage of two European Transmission System Operators. The resulting data were then validated, cleaned, and put in a structured format. Then we used two of R's graph packages to produce a couple of informative graphs which reveal the following insights:

- The Continental grid has a more stable frequency than the Nordic grid.
- The frequency quality is most strained around the change in hour and during ramping of production.
- The public data from the TSO's is not precise enough to serve as a grid clock (which should be possible for a frequency controlled clock that is directly connected to the grid), but we do observe reversals in the grid frequency which is consistent with an active frequency management aimed at keeping the long-run average frequency at 50 Hz.

Future Research / Links

For more information on grid frequency check ENTSOE.
In the "Network Code on Load-Frequency Control and Reserves" some commonly agreed measures of frequency quality are presented. It would be interesting to use these quality measures on the downloaded grid data to assert the formal frequency quality in the Continental and Nordic grids.