Technical Note

# Making Observations with Mode-357

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# Contents

# 1 Introduction

This document describes the use of 'multi-mode' — specifically Mode-357 – observations that can be made by any LOFAR station. This is where different RCU modes are used for different signal processing channels in order to make use of different frequency bands and, if required, both the LBA and HBA arrays. These modes were first demonstrated at KAIRA in September 2012 and have since been used for projects such as observing solar bursts or monitoring ionospheric scintillation.

## 1.1 Abbreviations

This section contains relevant references and definitions for the content of this document. See also the ASTRON documentation for additional definitions of terms [4].

| | |
|---|---|
| ACC | Array Covariance Cube (also Antenna Cross-Correlation; data product) |
| ASTRON | Netherlands Foundation for Radio Astronomy |
| BST | Beamlet Statistics (data product) |
| DSP | Digital Signal Processing |
| EISCAT | European Incoherent Scatter (scientific association) |
| FI609 | LOFAR station, Finland #609 (= Kilpisjärvi, LCU only) |
| HBA | High-Band Antenna |
| ILT | International LOFAR Telescope |
| KAIRA | Kilpisjärvi Atmospheric Imaging Receiver Array |
| KBT | KAIRA Background Task (scripting software) |
| LBA | Low-Band Antenna |
| LCU | Local Control Unit |
| LOFAR | Low Frequency Array |
| RCU | Receiver Unit |
| RFI | Radio-Frequency Interference |
| RSP | Remote Station Processing |
| RF-container | Shipping container, with Faraday cage for DSP electronics |
| SGO | Sodankylä Geophysical Observatory |
| SST | Subband Statistics (data product) |
| VHF | Very High Frequency |
| XST | Correlator Statistics (single-subband data product) |

## 1.2 References

The following is a table of material referenced within the text of this document.

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### 1.3 Acknowledgements

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## 2 Overview

Most LOFAR stations have two antenna fields. These are the Low-Band Antenna (LBA) array and the High-Band Antenna (HBA) array. The LBA and HBA antennas are capable of receiving a range of 10-90 and 110-270 MHz respectively. However, the signal processing is arranged slightly differently. Each "channel" in the signal processing system has three inputs into which the antennas are connected. These receiver units (RCUs), then have several signal paths that can be used, each of which switch in different filters. Thus, the different antennas and frequency bands can be selected and sampled [12].

Because each individual receiver unit has both an LBA and an HBA polarisation connected to it, it is not possible to observe with both of these simultaneously. Furthermore, because of the filters used in the RCUs, it is not possible to observe across the entire frequency range of the HBA simultaneously either. You must select one of these 'RCU modes' in order to specify the signal selection and processing that will occur.

The point is that each RCU is limited to a single mode. This has led some to believe that LOFAR stations cannot observe with the LBA and HBA simultaneously.

Actually... they can.

In September 2012, we began operations using a combination of modes. The first of these, and perhaps the best known, is what we refer to as "RCU mode 357". As the name suggests, this allows the station to observe with RCU modes 3, 5 and 7 simultaneously. The modes are interleaved, so that there is still a distribution of antennas for each; this allows beam-forming to take place.

Because of hardware limitations, one must be careful in mapping the channels and powering-up the HBA tiles in such a way so as not to cause power supply failures. However, when done correctly, multiple beams across all bands can be formed giving frequency coverage over nearly the entire VHF band.

## 3 Principle

Each KAIRA antenna has two outputs: X- and Y-polarisations. These are cabled back into the RF-container via coaxial cables where they are each connected to a Receiver Unit (RCU). Each RCU has three inputs. Typically for an international LOFAR stations, one input is used for a HBA polarisation, one input is used for a LBA polarisation and the third is left spare. On Dutch stations, which have a reduced set of RCUs, the LBA is split, with half using the second RCU channel and the other half using the third.

KAIRA has 48 antennas in each of the HBA- and LBA-fields. It also has 96 RCUs. This means that a regular observation would have the 48-antennas $\times$ 2-polarisations would be selected directly. For example, the RCUs would all be set to mode 3 in order to observe with the entire LBA.

The 'multi-mode" observations make use of different modes on different RCUs. That way different filters can be selected as well as different antennas (that is, from different arrays).

The trade-off is that only one input on a given RCU can be used at a given time. So, for example, if RCU 00 is the X-polarisation of LBA-aerial #00 and the X-polarisation of HBA-tile #00, then it is impossible to use those two simultaneously (without re-cabling the array!).

# 4 Planning observations

In order to design multi-mode experiments, it is necessary to decide the division between the different modes and the frequency bands that the observer wishes to cover.

## 4.1 Array layout

The layout of the LOFAR antennas at the KAIRA site is shown in Figure 1. The VHF arrow marks the azimuthal direction towards the VHF-transmitter at Ramsfjordmoen, near Tromsøin Norway, which is used is many of KAIRA's experiments.

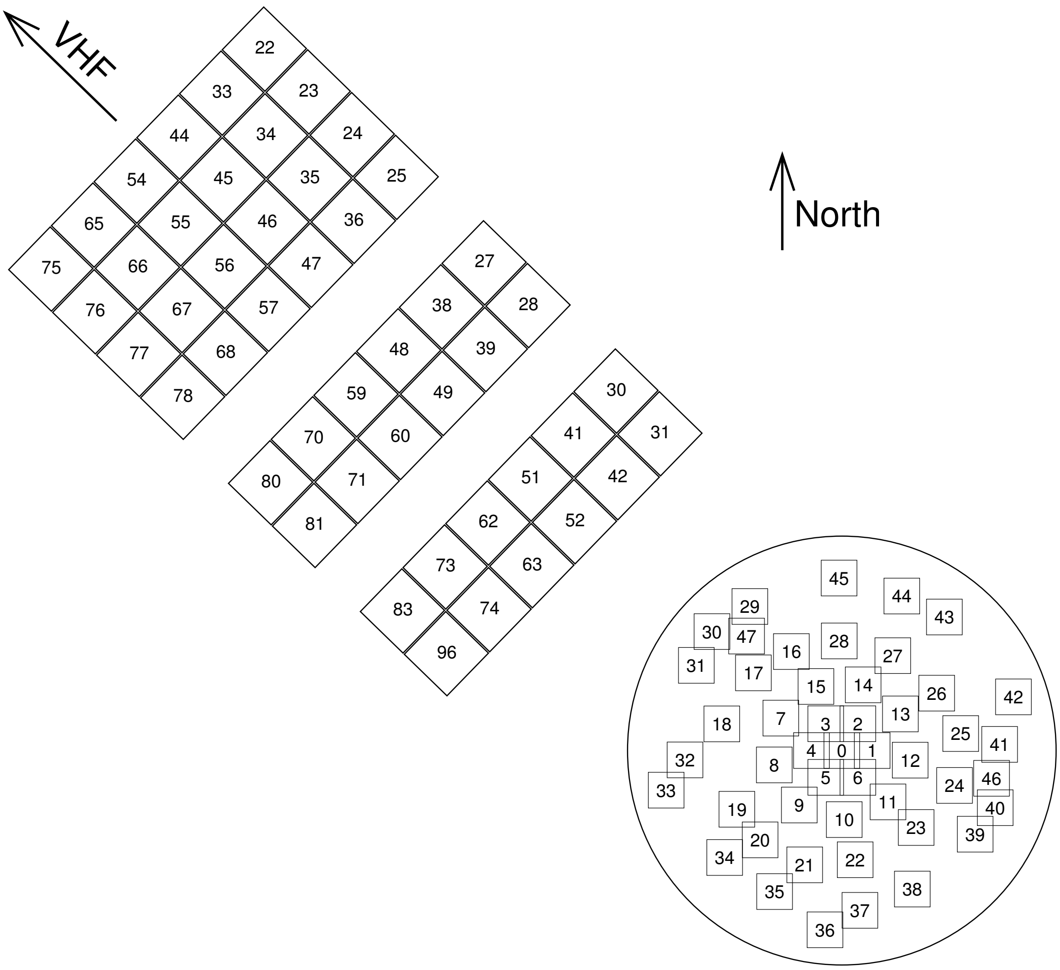


Figure 1: Scale layout of the KAIRA antennas [5].

The HBA array layout was chosen as a compromise between beam-pattern for imaging the region of the atmosphere illuminated by the EISCAT radar and ease of construction and maintenance in a heavy-snow region. The layout is consistent with a 96-antenna layout of a LOFAR international station, with the only exception being HBA #96, which is not coincident with any LOFAR layouts. While this permits KAIRA to be upgraded without requiring the repositioning of existing antennas, it does present a non-standard patching between HBA number and RCU number.

The LBAs are scattered in a quasi-random pattern across a field 34 metres in diameter to give a good beam-profile with low sidelobes. It roughly matches the layout of the inner section of a LOFAR remote station [3], thus facilitating direct comparison.

The match between the LBA and the RCU number is straight-forward, with antennas being assigned to each RCU in the same sequence order. This LBA #00 patches to RCUs 0 and 1; LBA #01 patches to RCUs 2 and 3; and so on [6].

However, because of the irregular nature of the HBA array, an irregular numbering system results. Although this numbering is consistent with an international station layout, it does result in a different patching sequence between HBA tiles and the RCUs. The match between the RCUs and the HBA tiles is given in Table 1.

| RCUs | LBA | HBA | RCUs | LBA | HBA | RCUs | LBA | HBA | RCUs | LBA | HBA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0,1 | 0 | 22 | 24,25 | 12 | 38 | 38,39 | 54 | 24 | 72,73 | 36 | 70 |
| 2,3 | 1 | 23 | 26,27 | 13 | 39 | 39,40 | 55 | 25 | 74,75 | 37 | 71 |
| 4,5 | 2 | 24 | 28,29 | 14 | 41 | 41,42 | 56 | 26 | 76,77 | 38 | 73 |
| 6,7 | 3 | 25 | 30,31 | 15 | 42 | 42,43 | 57 | 27 | 78,79 | 39 | 74 |
| 8,9 | 4 | 27 | 32,33 | 16 | 44 | 44,45 | 59 | 28 | 80,81 | 40 | 75 |
| 10,11 | 5 | 28 | 34,35 | 17 | 45 | 45,46 | 60 | 29 | 82,83 | 41 | 76 |
| 12,13 | 6 | 30 | 36,37 | 18 | 46 | 46,47 | 62 | 30 | 84,85 | 42 | 77 |
| 14,15 | 7 | 31 | 38,39 | 19 | 47 | 47,48 | 63 | 31 | 86,87 | 43 | 78 |
| 16,17 | 8 | 33 | 40,41 | 20 | 48 | 48,49 | 65 | 32 | 88,89 | 44 | 80 |
| 18,19 | 9 | 34 | 42,43 | 21 | 49 | 49,50 | 66 | 33 | 90,91 | 45 | 81 |
| 20,21 | 10 | 35 | 44,45 | 22 | 51 | 51,52 | 67 | 34 | 92,93 | 46 | 83 |
| 22,23 | 11 | 36 | 46,47 | 23 | 52 | 52,53 | 68 | 35 | 94,95 | 47 | 96 |

Table 1: RCU numbers and the equivalent LBA-aerials and HBA-tiles for the KAIRA station [9, 10].

The assignment of the antennas to RCUs for other LOFAR stations will vary. Patching information is usually provided as part of the station handover. However, the definitive list of antenna-location to RCU assignment is specified in the `AntennaField.conf` parameter file. Note that the use of the `AntennaArrays.conf` file (which was more convenient for humans to read) has now been deprecated. There are certainly been instances of obsolete versions of this file in LOFAR installations, so all observers and software developers are urged to use the actual specification that is used by the station: namely the `AntennaField.conf` file.

### 4.2 RCU modes

Table 2 shows the different RCU modes and what filter ranges they cover.

RCU mode 6 uses not just different filters, but also a different clock rate (160, rather than 200 MHz) in order to sample the frequencies around 200 MHz (which would normally be aliased in the other modes).

In principle, it is also possible to run some of the other modes with the 160 MHz clock. For some, this will not work effectively, as it will cause a mismatch between the Nyquist zone and the filters. For example, using RCU-mode 7 with the 160 MHz clock would not work effectively. However, LBA observations with RCU-mode 3 and the 160 MHz clock would be possible, resulting in a changed spectral resolution.

Although different clocks are available, only one may be selected for the entire array; it is not possible to mix the clock rates within a given observation, and changing between the two clock frequencies is a slow process.

| RCU mode | Input | Array | Filter range | Notes |
|---|---|---|---|---|
| 0 | – | – | – | *'off-position'* |
| 1 | LBL | LBA | 10-90 MHz | *Not used on KAIRA* |
| 2 | LBL | LBA | 30-90 MHz | *Not used on KAIRA* |
| 3 | LBH | LBA | 10-90 MHz | |
| 4 | LBH | LBA | 30-90 MHz | |
| 5 | HBA | HBA | 110-190 MHz | |
| 6 | HBA | HBA | 170-230 MHz | *Uses 160 MHz clock* |
| 7 | HBA | HBA | 210-270 MHz | |

Table 2: Filters used by the different arrays [11].

For the purposes of this document, we will limit ourselves to just the 200 MHz clock and consider the combination of RCU modes that gives maximum frequency coverage: modes 3, 5 and 7.

Within each mode, there are still 512 subbands, thus the selection of frequencies remains the same. Only the allocation of RCUs, and hence antennas, to the beamlets needs to be adjusted to ensure combination of only compatible data.

### 4.3 Experiment design

When designing the experiment, the trade-offs need to be balanced to ensure that the observations will achieve the desired goals. In particular there are certain points that must be considered.

Obviously, the use of sub-arrays means that the beam pattern for those sub-arrays will be major factor. Selecting combinations of antennas so that the beam patterns remain symmetrical, or that the beam patterns for different modes are comparable, may be important. To obtain matched beam sizes, longer LBA-array baselines would be required compared with the HBA-array, which has effectively a better spatial resolution due to the shorter wavelengths it receives.

Additionally, the response of the system in different modes may also affect the choice of how to split the arrays. Typically, HBA tiles will have a much better gain. Therefore, assuming sources with flat radio-sepctral index, fewer tiles would be required compared to the number of LBA aerials used.

However this gain increase comes at the expense of field-of-view. The tighter primary beam of and HBA tile may become a limiting factor in the number of sources that can be covered by a single experiment. This can be compensated using sub-tile selections (that is, not using all 16-cells in a given tile, thus resulting in a broader beam, but with reduced sensitivity).

Alternatively, temporal beam switching could be employed to toggle between different sources.

For beamlet to subband selection, the subbands do not need to be consecutive, thus allowing RFI to be avoided and a greater overall coverage of the frequency bands to be achieved. With new LOFAR systems, 8- and 4-bit modes may provide additional frequency coverage, although at the possible expense of dynamic range.

## 5 Taking observations in Mode-357

This section describes the detailed commands that are required for the taking of a Mode-357 observation. The experiment commands are all standard LOFAR control system commands and it is assumed that the reader is already familiar with them. A comprehensive description of the LOFAR data-taking system can be found in [11].

For KAIRA observations, it is strongly recommended that command sets are incorporated into KAIRA Background Task (KBT) scripts. Manually typing in commands is always fraught with danger as mistakes are easily made, especially on long-command line sets. KBT also provides the additional benefit of automated observer logging and data file management. However, any scripting environment can easily be used to create and run command lists.

### 5.1 Enabling the array antennas

The following LCU commands are used to enable KAIRA. It assumes that the system began at swlevel 0. Start by taking the system up to swlevel 3.

```
swlevel 3
```

This can take a little while, as the register commands needs time to complete. The system can be checked with commands such as:

```
swlevel
rspctl --regstat
rspctl --rcu
rspctl --status
```

In most automated scripts these are not necessary. In fact the last of the above commands (`rspctl --status`) requires user interaction to terminate it!

Once the system is at swlevel 3 and is ready to use, the next thing that is required is the activation of the different RCUs and antennas into the required modes. When setting an RCU mode for an antenna, this will (as required) power up the relevant antenna. This leads to a fairly important warning.

**WARNING : DO NOT ACTIVATE MORE THAN 16 HBA TILES AT A TIME**

Unlike the LBA units, the HBA tiles draw a reasonable amount of current. If you switch them on all at once, it may cause the power supplies to overload and trip out, thus taking out the station. Instead, you should leave a couple of seconds between each use of rspctl when activating antennas. This is why we need to use 'poweruphba.sh' when manually activating the HBA in a single RCU mode.

The following example activates the inner part of the LBA and two identical HBA tile stripes. Note the 2-second 'sleep' between activating the different modes.

```
rspctl --rcumode=3 --sel=0:31
sleep 2
rspctl --rcumode=5 --sel=32:63
sleep 2
rspctl --rcumode=7 --sel=64:95
```

Once the RCU modes have been set, then the RCUs can be enabled. Note that Mode 5 is an even Nyquist zone, so would typically require spectral inversion. Some example commands are:

```
rspctl --specinv=1 --sel=32:63
rspcel --rcuenable
```

Once this has been done, the station is active and in RCU mode 357. You can check the status of the RCUs by, for example, using the `rspctl --rcu` command.

## 5.2 Beam control commands

With the system now in 357-mode, commands can now be sent to control the pointing direction and allocation of subbands to beamlets. It is important to remember that the different mode sections need to be treated as sub arrays.

The next example, which follows from the commands in the previous section, shows how the `beamctl` commands are used to set the pointing directions. To ease in readability and code maintenance, variables are used for the directions. Although not really necessary for this example, it can be a very helpful technique when generating more complicated scripts with many pointings.

```
# Set up our pointing directions
CygA="5.23368658517913,0.710940948521916,J2000"
DIGDIR=$CygA
ANADIR=$CygA

# Send the commands to the system
beamctl --antennaset=LBA_INNER --rcus=0:31 --rcumode=3 \
        --subbands=200:299 --beamlets=0:99 --anadir=$ANADIR --digdir=$DIGDIR
sleep 1
beamctl --antennaset=HBA_JOINED --rcus=32:63 --rcumode=5 \
        --subbands=200:299 --beamlets=100:199 --anadir=$ANADIR --digdir=$DIGDIR
sleep 1
beamctl --antennaset=HBA_JOINED --rcus=64:95 --rcumode=7 \
         --subbands=200:243 --beamlets=200:243 --anadir=$ANADIR --digdir=$DIGDIR
```

Remember that the number of subbands and beamlets for a given beamctl command must always be the same. However, they no necessarily need to be consecutive and this can be used to generate a broader distribution of frequencies over the different bands. Additionally, the distribution does not need to be balanced. In the above example, there are 100 subbands/beamlets for each of modes 3 and 5, but only 44 subbands/beamlets for mode 7.

In 16-bit mode, the system is limited to 244 beamlets. However in 8-bit mode, it is possible to have up to 488 beamlets, thus giving more-or-less complete coverage of all available bands. Some examples of this have now been carried out by Fallows [1].

## 5.3 RSP data commands

Unlike array activation and the setting of the beamlets, data recording is essentially the same as other modes. Subband and beamlet statistics, along with station correlator products, can be recorded as per normal. For example:

```
nohup rspctl --statistics=beamlet --duration=86400 --integration=1 \
             --directory=/data/mydir > /data/mydir/rspctl_beamlet.log 2>&1
```

High-speed beamformed data can also be recorded. Note that if this is being done on an international station in single-station mode, that data streaming needs to be disabled to prevent the Groningen correlator from being flooded with data packets.

### 5.4 Terminating experiments

When the observation is complete, the station can be stopped in the usual manner. This can either be by shutting down, or reallocating beams. However, it is also typical to simply go to a reset state by setting the software level to zero.

```
swlevel 0
```

### 5.5 Creating generic experiment scripts

Because different LOFAR stations have a different number of antennas and RCUs, it may be necessary to create command sequences that can run easily on any station. This means automatically detecting the number of antennas/RCUs that exist at that particular site. The following is some example bash scripting which uses the `RemoteStation.conf` to determine whether the station has 96 or 192 RCUs (defaulting to 96, if it can't tell).

```
#  Detecting how many RCUs and RSP boards are available
if [ -e /opt/lofar/etc/RemoteStation.conf ]; then
  #  Detected RemoteStation.conf
  let RSPBOARDS=‘sed -n ’s/^\s*RS\.N_RSPBOARDS\s*=\s*\([0-9][0-9]*\).*$/\1/p’\
                 /opt/lofar/etc/RemoteStation.conf‘
  let RCUS=$RSPBOARDS*8
else
  #  Could not find /opt/lofar/etc/RemoteStation.conf
  let RSPBOARDS=12
  let RCUS=$RSPBOARDS*8
fi
echo "RSPBOARDS = $RSPBOARDS"
echo "RCUS = $RCUS"
```

With these variables, it is possible to then make case-dependent code. For example, the following code was tested at both KAIRA and LOFAR station UK608 (Chilbolton, UK).

```
rspctl --rcumode=3 --sel=0:31
sleep 2
rspctl --rcumode=5 --sel=32:63
sleep 2
rspctl --rcumode=7 --sel=64:95
sleep 2
```

```
if [ $RCUS -eq 192 ]; then
  rspctl --rcumode=3 --sel=96:127
  sleep 2
  rspctl --rcumode=5 --sel=128:159
  sleep 2
  rspctl --rcumode=7 --sel=160:191
  sleep 2
fi

#  Do required spectral inversions
rspctl --specinv=1 --sel=32:63
if [ $RCUS -eq 192 ]; then
   rspctl --specinv=1 --sel=128:159
fi
```

### 5.6 Other multi-mode observations

Of course, one is not limited to only mode-357; other 'multi-mode' observations are also possible.

For Dutch stations, there is a different arrangement of the RCUs with respect to the antennas, meaning that modes 1 or 2 may be required to get different intra-station array layouts. Additionally, work planned for the UK608 LOFAR station (Chilbolton), where four additional LBAs are added to the array, will mean that a similar technique is required, even for solely-LBA-based observations.

## 6 Data reduction

The LOFAR data formats are described in [11]. Note that since early-2013, most LOFAR stations have been upgraded to version v8.2 of the control software. Thus the arrangement of product files is now such that no partial products are present.

As with any multi-beam experiment, care must taken to select the correct data from the statistics files. Beamlets from different modes will also likely have drastically different responses and so initial 'first-look' plots may seem incorrect. Usually normalising to the channel median can be a good way to overcome this for rapid inspection of data products. In the long term, separate calibrations applied to the data will resolve any discontinuities.

For the ACC and XST files generated by the station correlator, only baselines with common modes will have meaningful visibilities.

As with all observations it is important to establish the correct frequency conversion between the subband number and the physical frequency in MHz.

To do this, multiply by the sampler clock, and divide by 2 and the number of subbands. This gives the lower edge of the subband. To get the top end of the subband, use (subband + 1) and, for the middle frequency of the subband, you need to use (subband + 0.5). It is this middle frequency that is usually required. Thus:

$$\nu_{\text{mid}} = \frac{(s + 0.5) \times \nu_{\text{clk}}}{2 \times 512} \tag{1}$$

where $\nu_{\text{mid}}$ is the centre-freqency of the subband and $\nu_{\text{clk}}$ is the clock frequency.

# 7 Sample results

Figure 2 is an example data set taken at KAIRA, plotting beamlet power at given frequencies as a function of time. Because of the configuration of the beamlets, nearly complete coverage of the VHF band was achieved.

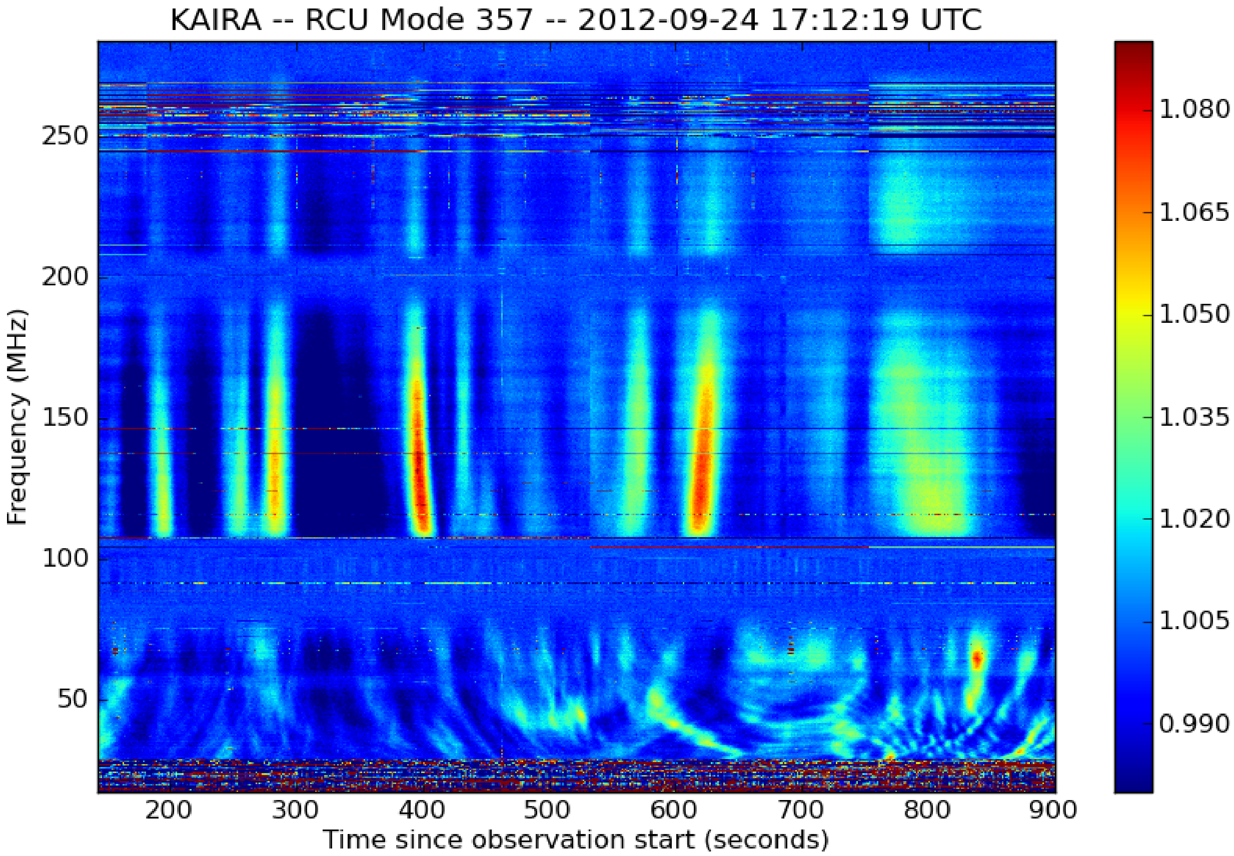


Figure 2: ‘First-light’ plot for mode-357 on KAIRA.

The horizontal striping is due to RFI and the different antenna and filter responses. In particular, the faded sections at 100 and 200 MHz are due to the anti-aliasing filters used to select the different Nyquist zones for the modes. The ‘speckled” horizontal lines (for example at approx. 20 and 260 MHz are RFI.

The broad vertical banding is, primarily, ionospheric scintillation.

# 8 Conclusion

Multi-mode observing with LOFAR stations is a powerful technique that can be used to achieve additional capability. It requires some care when setting up but, if scripted, can easily become a simple and effective tool for broad-band or other specialised observations.