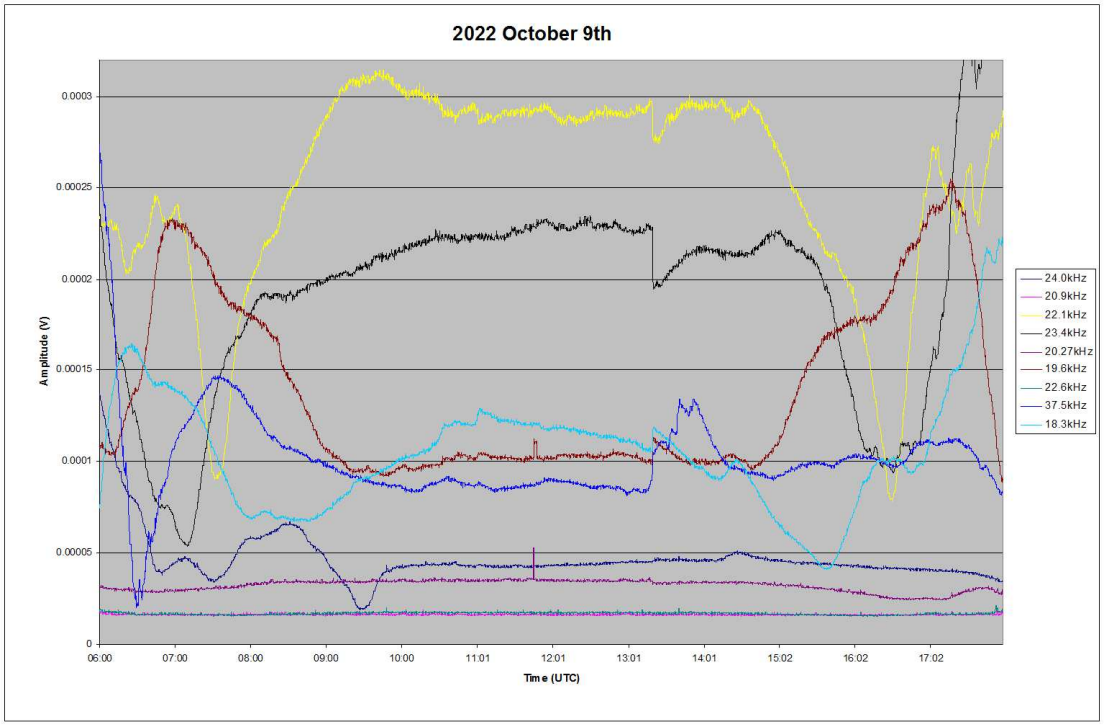
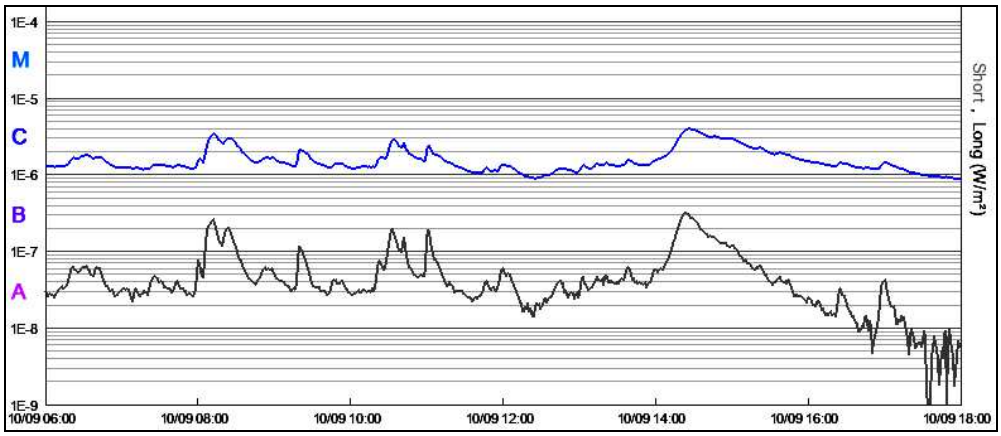
A Bolt from the Blue

Working through my VLF data for October 2022 I came across this plot for October 9th:-



At first glance there was nothing unusual. There was an obvious SID just after 13:00 and one or two less obvious ones around 11:00 and 14:30.



However, when compared with the corresponding plot of X-ray emission from the Sun as measured by the GOES satellite (above), the minor SIDs had corresponding peaks in the X-ray emission, the obvious one did not.

There are other possible sources of SIDs and one of these is a CME (Coronal Mass Ejection). This looked likely as the broad disturbance at 37.5kHz was similar to previous CMEs. Again there was no such event.

Still puzzled, I started to consider more unlikely events such as a volcanic explosion like the one in Tonga on 15th January 2022 which sent a wave through the ionosphere, or more worrying ones such as an atomic explosion. Thankfully, these also drew a blank, but there was a further possibility, which given the size of the SID seemed even more unlikely and that

was a GRB (Gamma Ray Burst). These had been seen to produce SIDs, but from what I had read they had been weak and very rapid, whereas this one lasted the best part of half an hour.

It was at this point that I came across this:-

```
TITLE:   GCN CIRCULAR
NUMBER:  32636
SUBJECT: GRB 221009A: Fermi GBM detection of an extraordinarily
bright GRB
DATE:    22/10/09 20:54:36 GMT
FROM:    Peter Veres at UAH  <veresp@gmail.com>

P. Veres (UAH),  E. Burns (LSU), E. Bissaldi (Politecnico and INFN
Bari), S. Lesage (UAH), O. Roberts (USRA)
report on behalf of the Fermi GBM Team:

"At 2022-10-09 13:16:59.000 UT on 9 October 2022, the Fermi Gamma-Ray
Burst Monitor (GBM) triggered and located GRB 221009A (trigger
687014224 / 221009553).
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This looked promising, except that the start time of the SID was 13:20:18 some 199 seconds later than the trigger time of 13:16:59. Reading on, though, in the circular:-

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The GBM light curve consists of an initial ~10 s long pulse, followed
by an extraordinarily bright episode at ~180 s after the trigger
time, lasting at least 100 seconds.
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It seems that GRBs have a precursor emission of X-rays that come several seconds before the main gamma ray burst. The Fermi satellite had triggered on that X-ray precursor and it looked as though the time of the SID would match the burst of gamma rays. That was further confirmed by this later circular:-

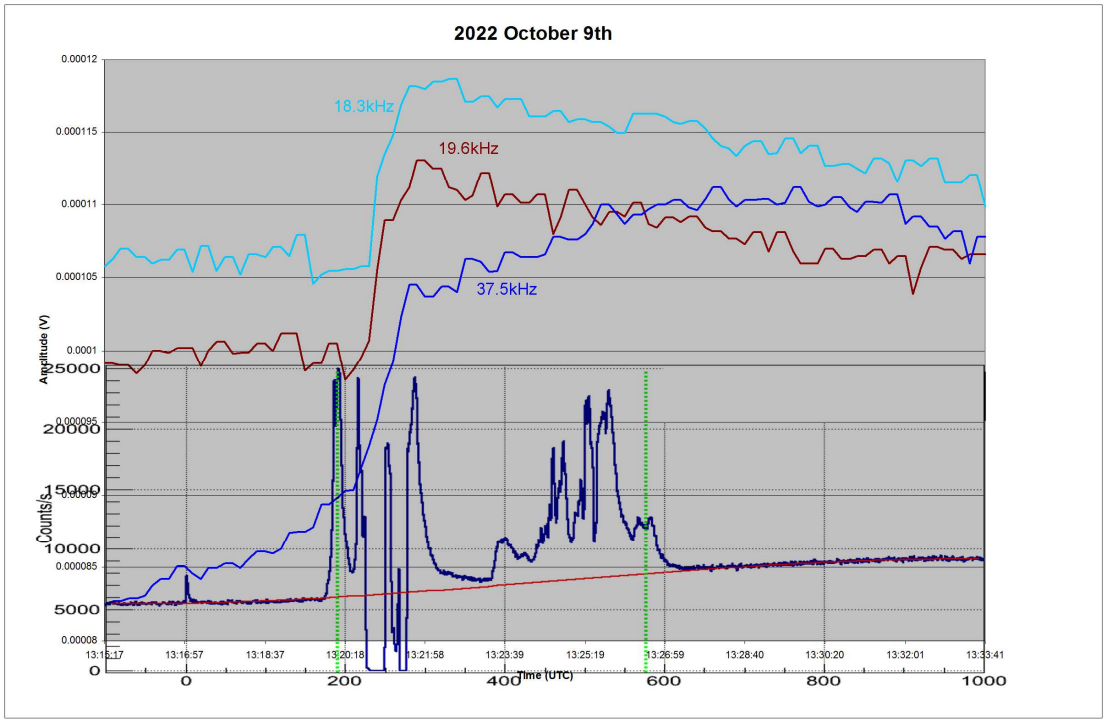
```
TITLE:   GCN CIRCULAR
NUMBER:  32658
SUBJECT: GRB 221009A: Fermi-LAT refined analysis
DATE:    22/10/10 13:42:46 GMT
FROM:    Roberta Pillera at Politecnico and INFN Bari
<roberta.pillera@ba.infn.it>

The LAT lightcurve shows a bright structured emission episode
which is temporally coincident with the GBM main emission episode
starting at T0+200s.
```

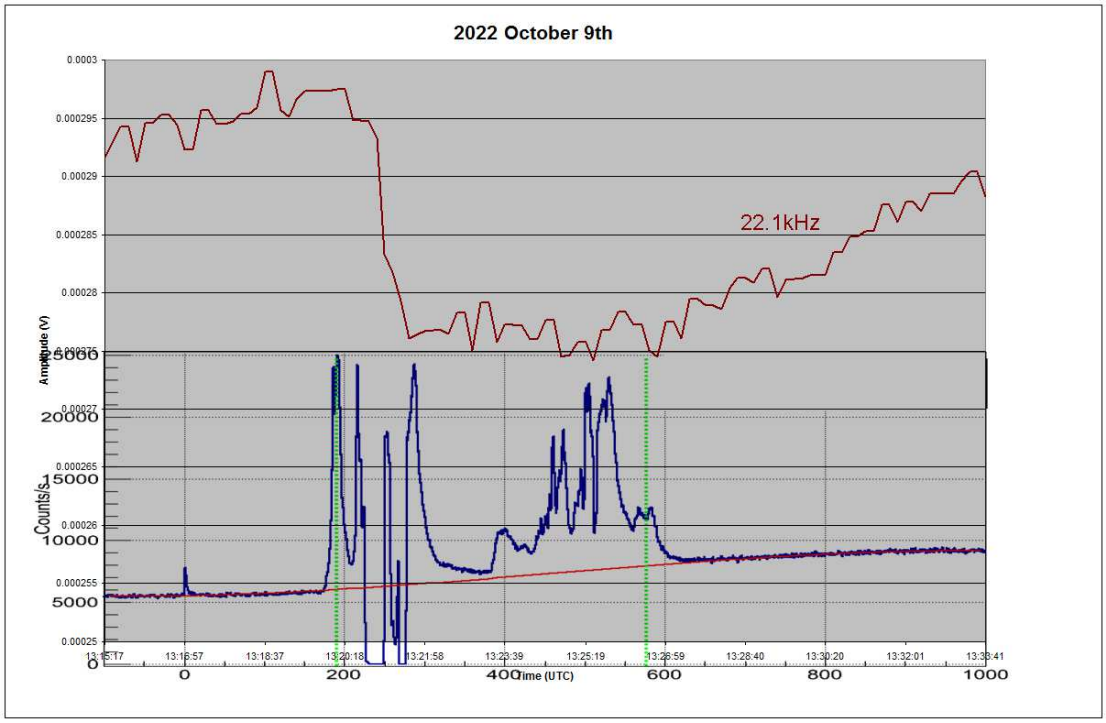
which aligned the times precisely.

The Insight-HXMT satellite also observed the precursor and the main burst. The burst was so bright that it saturated the detector and as a consequence data was lost at the peak (seen as zero counts in the plot below).

Overlaid onto the plot is an expanded view of three of the VLF frequencies showing that the steep rise in their amplitude coincided with the peak of the burst.



The 22.1kHz frequency also showed evidence of the second burst as a second drop in its amplitude as shown in the next chart. This was also the case at 23.4kHz.



In the way that the different frequencies registered the GRB there were a couple of anomalies. The first was the very weak effect at 24.0kHz. This comes from the transmitter at Cutler on the east coast of the USA and due to the multiple reflections of the skywave from the ionosphere is usually very sensitive to weak solar flares. It registered the flare at 14:28 comparable to the other frequencies, so why the weak response to the GRB?

I believe the answer to this can be found in the position of the GRB:-

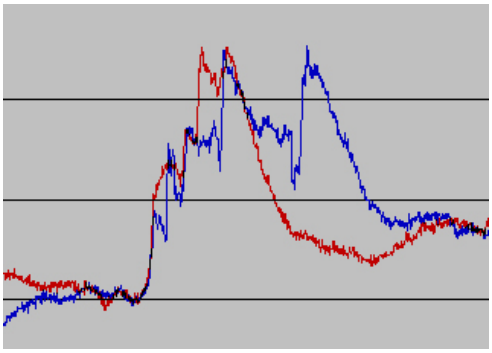
```
TITLE:   GCN CIRCULAR
NUMBER:  32688
SUBJECT: GRB 221009A (Swift J1913.1+1946): Swift-BAT refined analysis
DATE:    22/10/11 14:12:57 GMT
FROM:    Amy Lien at GSFC  <amy.y.lien@nasa.gov>

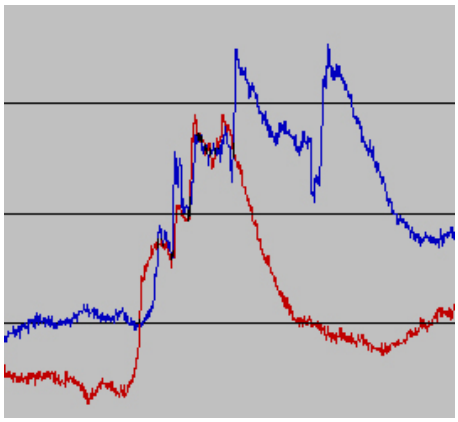
The BAT ground-calculated position is
RA, Dec = 288.254, 19.809 deg which is
   RA(J2000)  =  19h 13m 00.9s
   Dec(J2000) = +19d 48' 34.1"
with an uncertainty of 2.4 arcmin, (radius, sys+stat, 90%
containment).
```

At the time of the major burst, this position placed the GRB at an altitude of only 6 degrees in the east at the mid-point of the path to Cutler with part of the western part of the path unable to see the GRB at all. Compare this to the 30.5 degrees altitude of the Sun at the time of the solar flare.

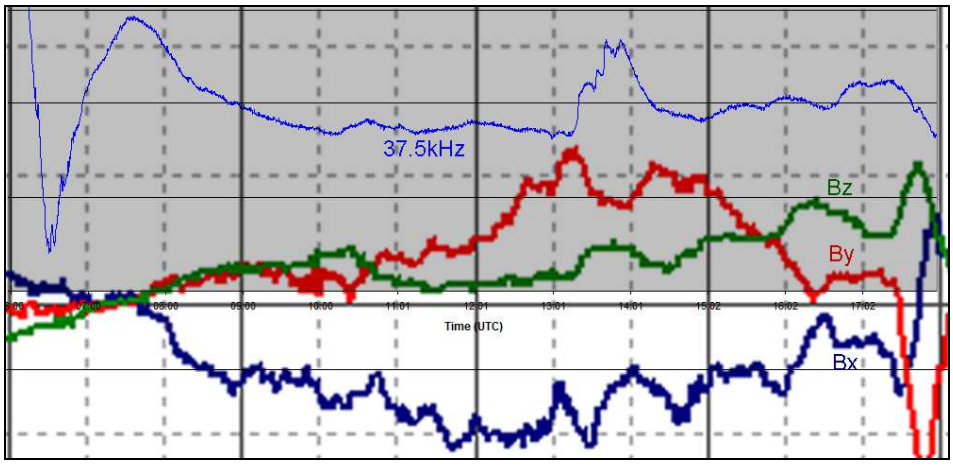
The other anomaly was that of the shape of the SID at 37.5kHz on the path to Iceland. Whereas the sharp rise in its amplitude occurred at the same time as the other frequencies, it started to rise before the precursor and rather than decline gradually after the burst continued to rise in a series of peaks and troughs.

This pattern is remarkably similar to that seen on 13th March 2022 when a CME hit the ionosphere. In the plots below the red trace is the GRB and the blue trace the CME. In the first one the starts of the SIDs are aligned and in the second the first trough is aligned.

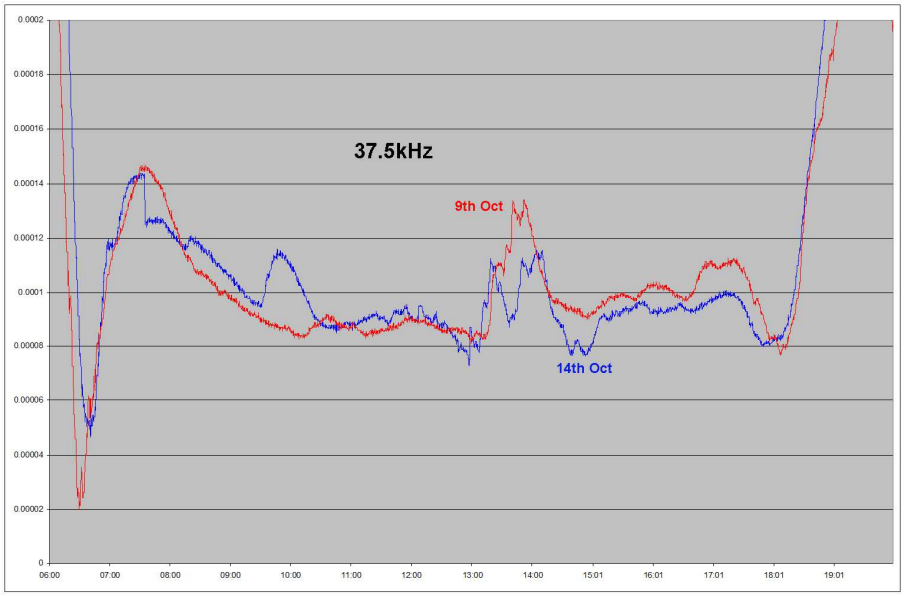




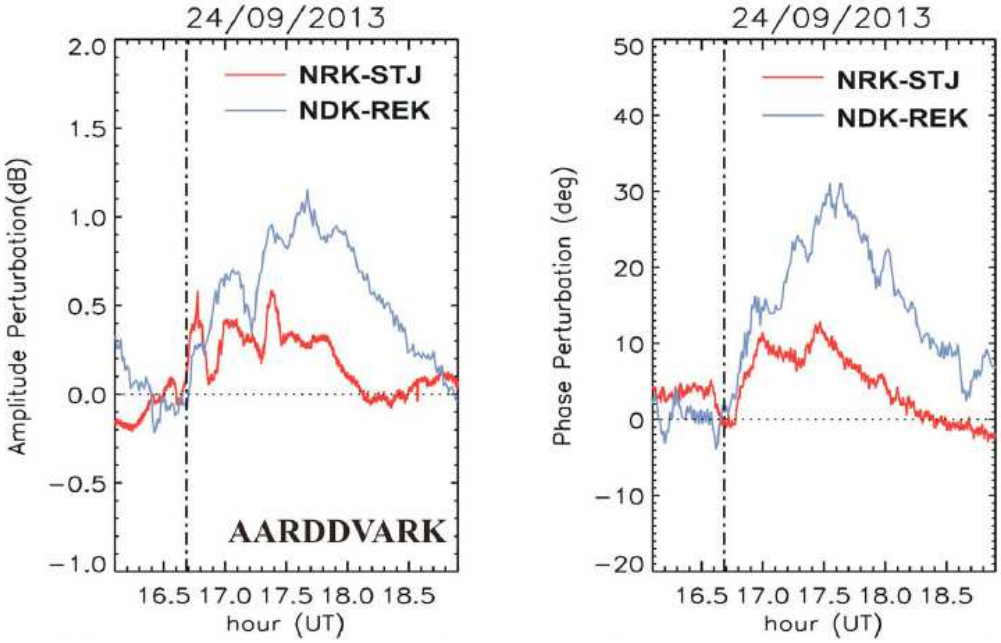
Also comparing the GRB SID with a plot of the Earth's magnetic field shows a feature that does appear to occur at the same time, as seen in the chart from Roger Blackwell:-



It would seem that the GRB induced a wave of ionisation in the ionosphere that affected the Earth's magnetic field. However, to complicate the issue further, on 14th October 2022 a similar 37.5kHz SID occurred without a GRB at almost the same time as that on the 9th. Again (as can be seen in the chart below), it shared some similar features.



Trying to find an explanation for this I came across an article in Geophysical Research Letters which showed the effects of electron precipitation from the Earth's magnetosphere on VLF amplitudes and phases to and from Iceland. These are shown in the charts below:-



Once more showing similar features. So it could be that all the effects seen at 37.5kHz could be due to that one source (CMEs are known to trigger precipitations) and as a consequence would look alike. If that is the explanation, it begs the question: Did the GRB produce the electron precipitation or was it a coincidence that the GRB happened just as an unrelated precipitation event got underway?