Geomagnetic Sudden Impulses

Whitham D. Reeve © 2013 W. Reeve

1. Introduction

This article discusses geomagnetic sudden impulses observed with the SAM-III magnetometer system at Anchorage, Alaska USA during the 12 month period 1 June 2012 through1 June 2013. A sudden impulse occurs when a coronal mass ejection (CME, figure 1) from the Sun collides with Earth's magnetosphere. A CME is a portion of the Sun's upper atmosphere (corona) that is accelerated into space by an explosive release of energy related to instabilities in the Sun's magnetic field. Many solar flares have a CME associated with them, but not all CMEs are related to flares. CMEs mix with the solar wind and carry with them threads of the Sun's magnetic field. Of course, only CMEs that are directed at Earth disturb Earth's magnetic field.

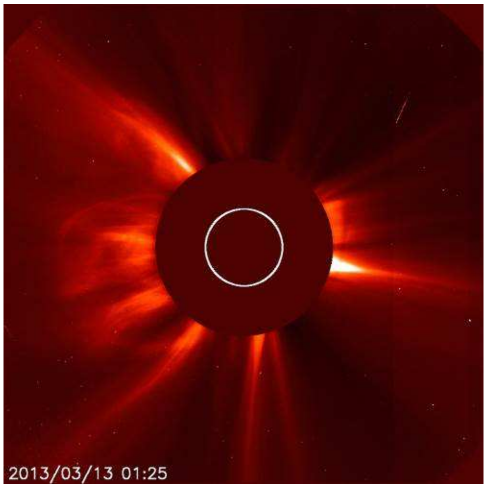


Figure 1 ~ Coronal mass ejection captured by ESA and NASA's Solar Heliospheric Observatory (SOHO) spacecraft as it bursts off the left side of the image on 12 March 2013. The occulting disk blocks the bright Sun so dimmer features around it may be seen. The white circle represents the Sun's size behind the disk. Image courtesy ESA and NASA/SOHO

The frequency of coronal mass ejections is related to the sunspot cycle, with the highest frequency occurring during the peak of the cycle. CMEs often travel faster than the ambient solar wind but not always. CME speeds exceeding 1800 km/s have been measured, but the highest percentage is in the 300 to 400 km/s range. In the period covered by this article, the CME speeds varied from 421 to 844 km/s and required 49 to 99 hours to reach Earth. The ambient solar wind speed depends on the sunspot cycle and varies from around 400 to 500 km/s. For additional information on CMEs, see [Knipp] and [Reeve] listed in **References and Further Reading**.

When the CME arrives it compresses Earth's magnetosphere, increasing the ring current and the horizontal component of the magnetic field along with it (the horizontal component is parallel to Earth's surface). This increase appears as a spike on terrestrial magnetometers (figure 2), appearing simultaneously within a few minutes around the world. Depending on the orientation of the interplanetary magnetic field (IMF) with respect to Earth's field, there may be considerable follow-on magnetic disturbance. If the IMF has a significant southward component a process called magnetic reconnection occurs, in which the magnetic field carried with the CME connects to and disconnects from Earth's field. This process can lead to a disturbance called a geomagnetic storm that can be quite strong and last for several days.

Measuring and predicting geomagnetic storms has become increasingly important in the last decade. A geomagnetic storm may negatively affect electric utility transmission lines, metallic pipeline currents, radio propagation and spacecraft including global navigation satellite systems (GNSS) such as the familiar Global Position System (GPS). Visible aurora also is directly linked to geomagnetic storms. In the United States, the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) provides a space weather scale for geomagnetic storms (http://www.swpc.noaa.gov/NOAAscales/) and attempts to predict them.

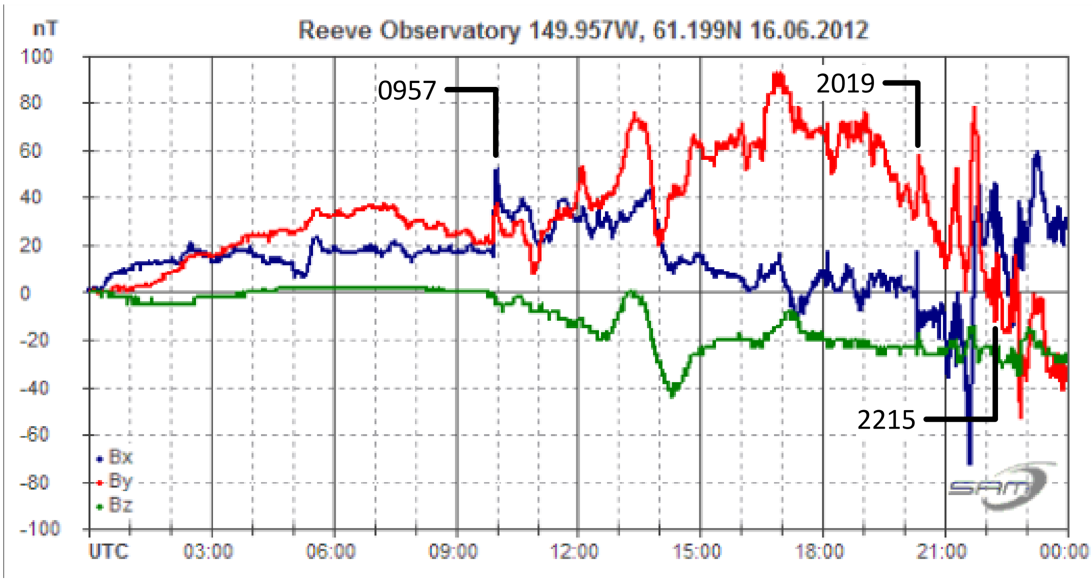


Figure 2 ~ Sudden impulses as seen on a magnetogram have a fast rise time and (usually) slower fall time as seen here (the times of three impulses are annotated). The most significant amplitude changes occur in the horizontal components, X and Y (blue and red traces), but occasionally large deviations also are seen in the vertical component, Z (green trace). In this magnetogram, Earth's field became increasingly disturbed as each of the three CMEs arrived.

2. Equipment

The SAM-III is based on the original Simple Aurora Monitor (SAM). The SAM originally was designed to warn of impending aurora associated with geomagnetic activity and provided 1- or 2-axis measurements. The SAM-III expanded that to 3-axis (figure 3). The SAM-III can be used in a stand-alone mode with or without a serial data recorder or connected to a PC for logging and plotting. The SAM-III at Anchorage is setup to sample magnetic field data at 0.1 Hz rate (10 second sample period). It may be setup to sample periods from 1 to 120 seconds.

Figure 3 ~ SAM-III processor (left) includes a 4X20 liquid crystal display and pluggable connectors for the magnetic field sensors. The dimensions are 200 mm x 112 mm x 64 mm and power requirements are nominal 12 Vdc at 100 mA. Sensors (two shown right) are about 61 mm long.

A block diagram shows the basic hardware components (figure 4). Additional details can be found at: http://www.reeve.com/SAMDescription.htm. For reference, the resolution of the SAM-III is around 1 or 2 nT, and the average magnetic flux density (magnetic induction) of Earth's main field at the equator is about 32000 nT.

The SAM-III has a battery-backed internal real-time clock but it is not synchronized to UTC and will slowly drift. At the time of the most recent measurements, it was running 3 minutes fast and had not been reset in about 2.5 years. This time offset is apparent in most of the individual sudden impulse plots shown later. When Space Weather Prediction Center reports impulse times, they are given to the nearest minute.

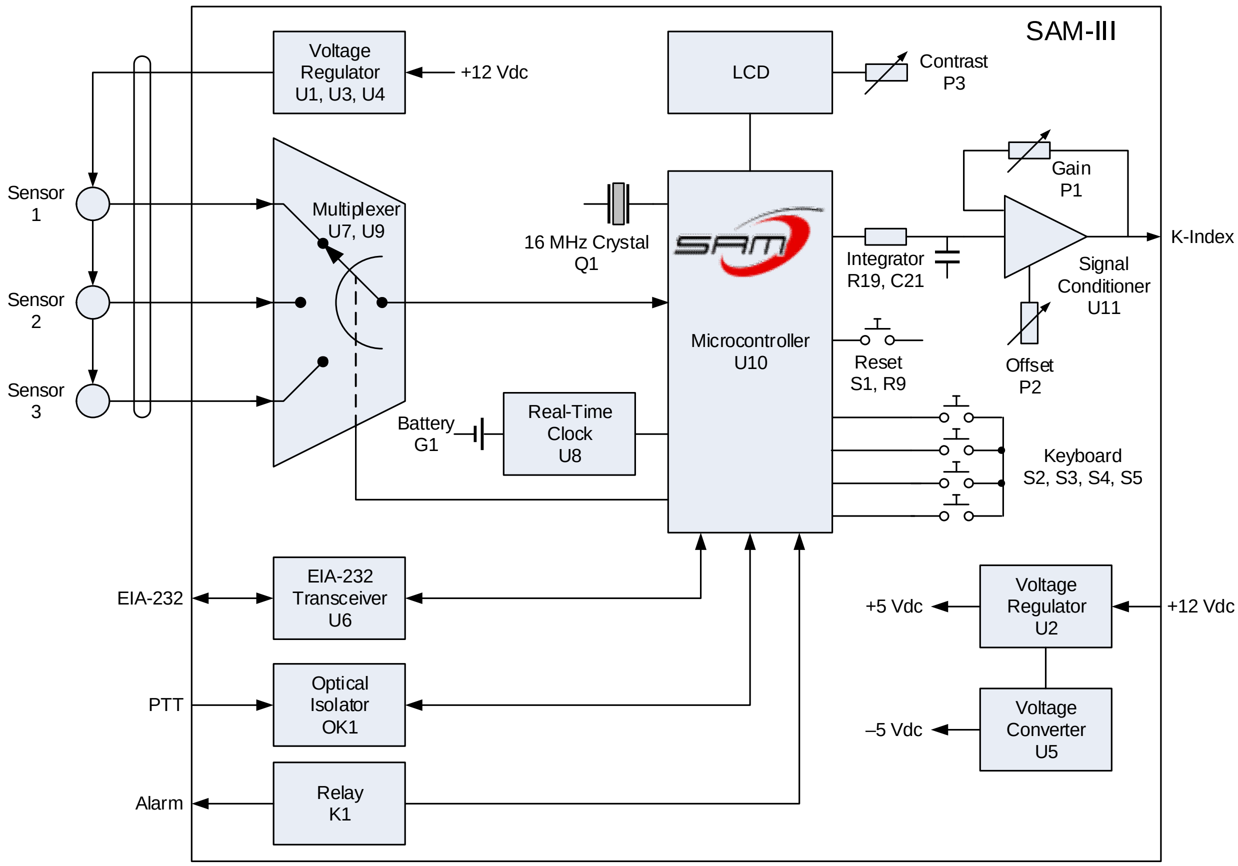


Figure 4 ~ SAM-III block diagram. The signal output from the three sensors is multiplexed and then measured by the counter function in the microcontroller. The values are then scaled and formatted before sending through the EIA-232 serial port to a serial data recorder or PC running SAM_VIEW software. Other functions include an alarm output, K-index output and push-to-talk input to disable and prevent erroneous measurements when a nearby transmitter is keyed.

3. Observations

All observations were taken at Anchorage, Alaska, geographic latitude 61°N and geomagnetic latitude 62°N, at the southern edge of the auroral oval. Natural variations in Earth's magnetic field increase with higher latitudes, sometimes making it difficult to recognize a weak sudden impulse on a magnetogram. I bypass this problem by using warnings and alerts issued by SWPC, which are based on observations at approximately 40°N latitude. When the shock associated with an Earth-directed CME is observed at the Advanced Composition Explorer (ACE) spacecraft, located about 1.5 million km from Earth in line with the Sun, SWPC issues a warning within a few minutes. The CME will impact the magnetosphere about 30 to 60 minutes later depending on its speed. When the collision occurs, SWPC issues an alert giving the time it is observed on Earth. It is this time that allows me to correlate and confirm my observations.

In the 12-month period 1 June 2012 to 1 June 2013, twenty-two shocks were observed at the ACE spacecraft of which twenty-one were observed as sudden impulses at Anchorage, Alaska and Boulder, Colorado (table 1).

There were two months with no sudden impulses (August and December 2012). The impulse amplitudes ranged from 8 to 48 nT, and the average amplitude was approximately 24 nT with a standard deviation of about 10 nT.

Table 1 ~ Tabulation of sudden impulse observed at Anchorage, Alaska from 1 June 2012 to 1 June 2013

Event	Date-Time-Lv (mm/dd/yy hhmm)	Time-IP Shock (mm/dd/yy hhmm)	Date-Time-Ar (mm/dd/yy hhmm)	Elapsed Time-ACE (h:mm)	Time-Enroute (h)	Average CME Speed (km/s)	Sudden Impulse Amplitude (nT)
1	06/13/12 1317	Not available	06/16/12 0957	Not available	68.7	607	28
2	06/13/12 1317	06/16/12 1931	06/16/12 2019	0:48	79.0	527	28
3	06/14/12 1435	06/16/12 2031	06/16/12 2115	0:44	54.7	762	25
4	07/12/12 1649	07/14/12 1728	07/14/12 1811	0:43	49.4	844	27
5	08/31/12 2043	09/03/12 1123	09/03/12 1214	0:51	63.5	656	28
6	09/13/12 0640	09/16/12 0350	Not available	Not available			Not available
7	09/28/12 0018	09/30/12 1025	09/30/12 1138	1:13	59.3	702	15
8	09/28/12 0018	09/30/12 2213	09/30/12 2307	0:54	70.8	588	35
9	10/05/12 0730	10/08/12 0430	10/08/12 0515	0:45	69.8	597	21
10	10/27/12 1235	Not available	10/31/12 1539	Not available	99.1	421	13
11	11/09/12 1230	11/12/12 2220	11/12/12 2316	0:56	82.8	503	16
12	11/21/12 1530	11/23/12 2112	11/23/12 2156	0:44	54.4	765	25
13	11/23/12 1200	11/26/12 0437	11/26/12 0514	0:37	65.2	639	8
14	01/16/13 1900	01/19/13 1647	01/19/13 1733	0:46	70.6	591	21
15	Unknown	02/16/13 1058	02/16/13 1210	1:12			10
16	03/12/13 1107	03/15/13 0442	03/15/13 0526	0:44	66.3	628	23
17	03/15/13 0712	03/17/13 0528	03/17/13 0601	0:33	46.8	890	48
18	04/11/13 0716	04/13/13 2215	04/13/13 2255	0:40	63.7	655	29
19	05/15/13 0148	05/18/13 0023	05/18/13 0112	0:49	71.4	584	31
20	05/17/13 0912	05/19/13 2221	05/19/13 2306	0:45	61.9	673	39
21	05/22/13 1332	05/24/13 1735	05/24/13 1812	0:37	52.7	791	18
22	Not available	05/31/13 1531	05/31/13 1618	0:47			9
Key Ar = Arrive , Lv = Leave			**Averages**	0:48	66.5	654	23.7
			Standard Dev	0:10	12.4	118	10.1

Table notes:
1. **Time-IP Shock** is when the inter-planetary CME shock passes the ACE spacecraft.
2. **Elapsed Time-ACE** is from the inter-planetary shock measured at ACE to the sudden impulse measured on Earth's surface.
3. **Time-Enroute** is the difference between the arrival date-time (sudden impulse time) and leave date-time.

4. Magnetograms

Magnetograms are shown for each of the twenty-one sudden impulses listed above (figure 5, a through r). The magnetograms are annotated to show the time reported by SWPC for each sudden impulse. The SAM-III measures the absolute value of the magnetic field, but the SAM-III magnetograms show the relative change in Earth's magnetic field components, X, Y and Z (a geographic reference system is used) with respect to their values at 2359 UTC the day before (that is, the plots are normalized at the beginning of each day). Magnetic induction is measured in nanoTeslas (nT, vertical scale) and plotted with respect to Coordinated Universal Time (UTC, horizontal scale).There are a few characteristics worth mentioning:

1. Most sudden impulses are followed for several hours by a significant increase in magnetic activity (note the vertical scales; for comparison, on a quiet day the variation is perhaps ±10 nT at my observatory).

2. Many post-impulse disturbances have an oscillatory nature. When magnetic reconnection occurs, energy from the solar wind enters the magnetosphere and is transported to the night side where it is temporarily stored in the magnetosphere's tail. As the energy builds up, it reaches a threshold and is released and some energy is directed back toward Earth. The storage process starts again until the threshold is reached and the energy is released. This cycle is called a substorm and typically has a period of 1 to 3 hours.
3. In those cases when more than one sudden impulse occurs within a 24 hour period, later impulses are buried in the increased activity from previous impulses.
4. The sudden impulses mostly affected the horizontal component of Earth's magnetic field, but some impulses also affected the vertical (Z) component, possibly due to induced magnetism. Generally, the Y-component (east-west) is affected the most.
5. The sudden impulse amplitude shows some correlation with the speed of the associated coronal mass ejection (faster speed → higher amplitude).

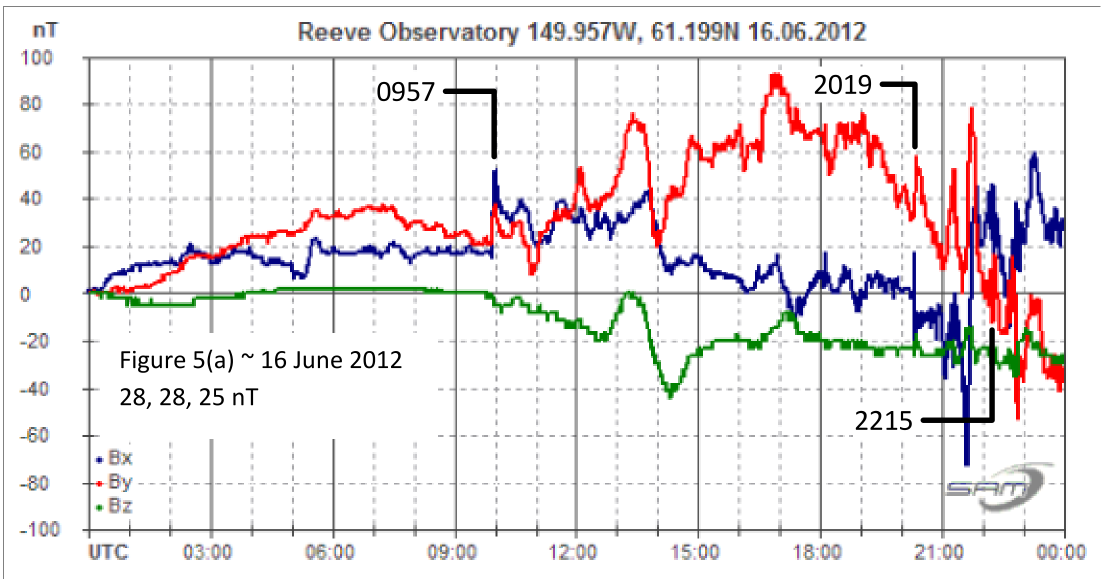


Figure 5(a) ~ 16 June 2012
28, 28, 25 nT

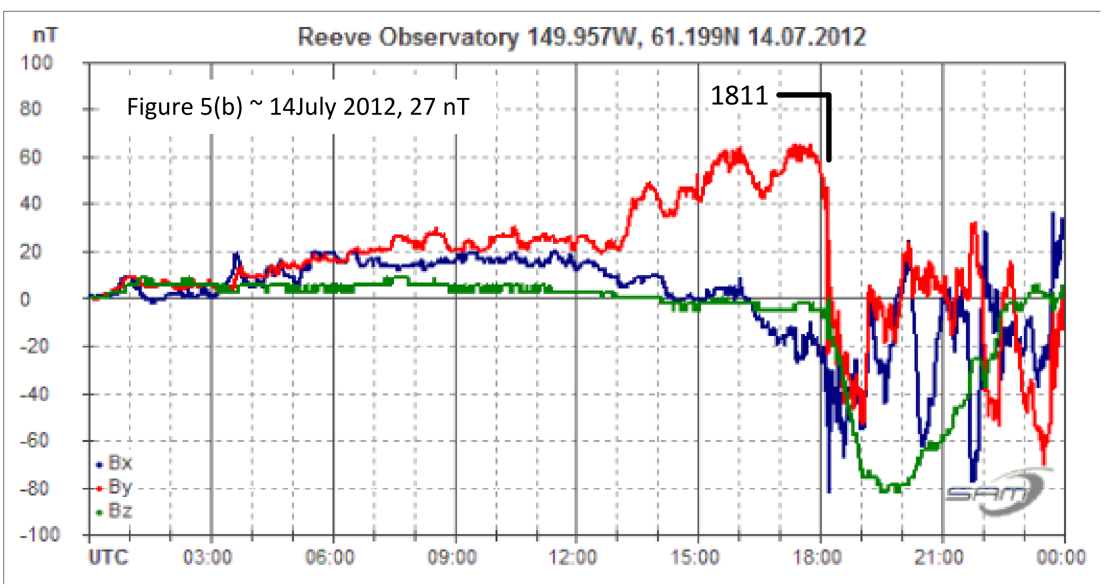
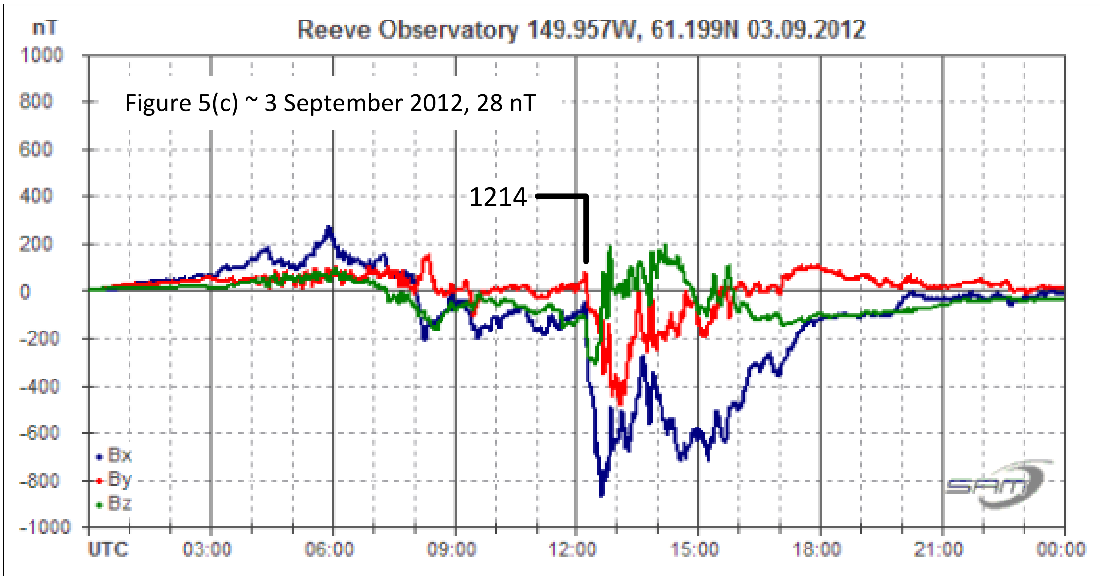
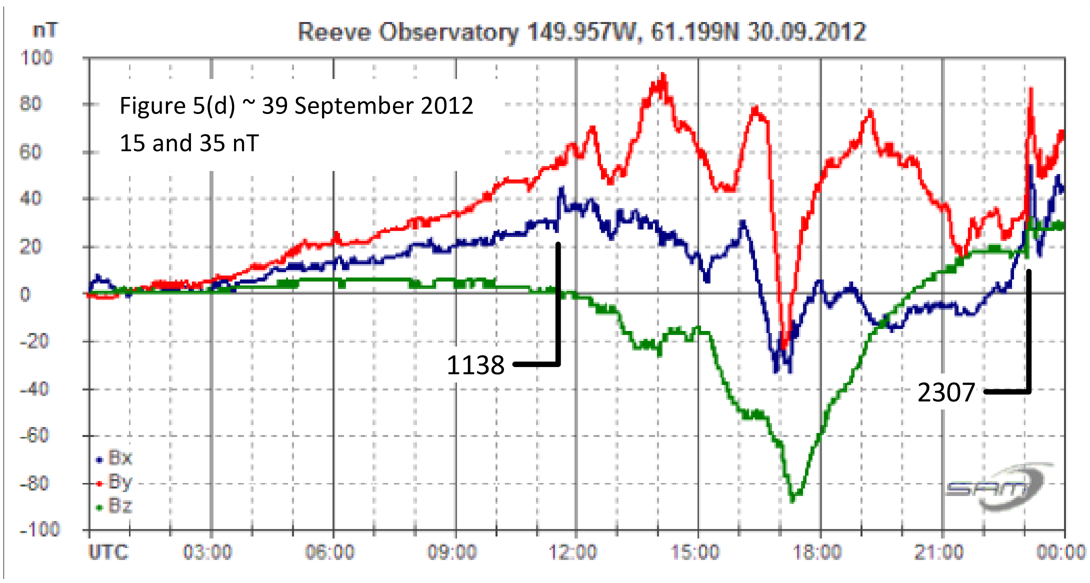
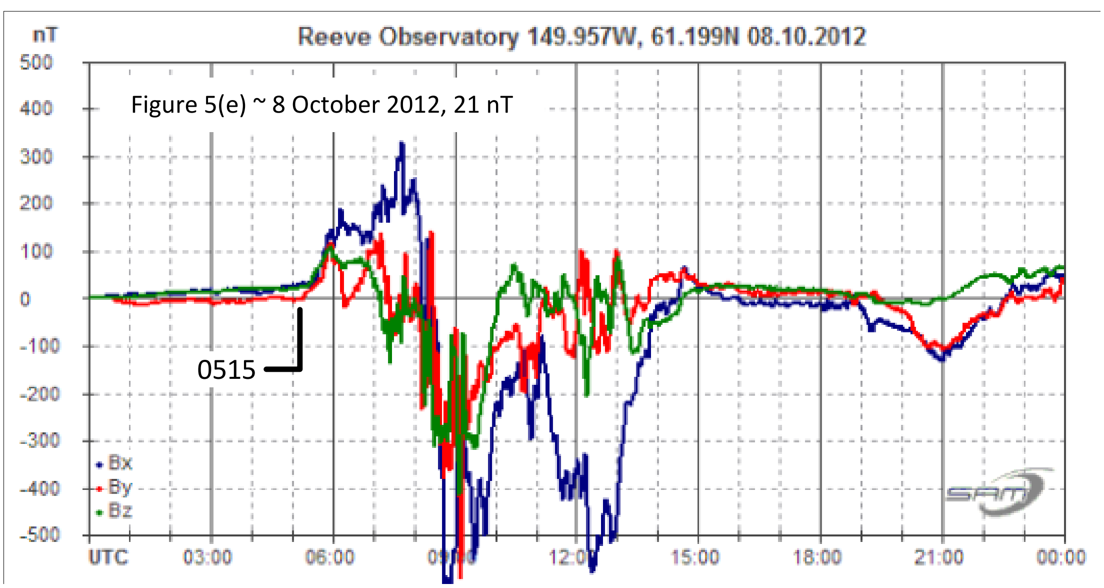


Figure 5(b) ~ 14July 2012, 27 nT


Reeve Observatory 149.957W, 61.199N 03.09.2012
Figure 5(c) ~ 3 September 2012, 28 nT
1214
nT
Bx
By
Bz
UTC


Reeve Observatory 149.957W, 61.199N 30.09.2012
Figure 5(d) ~ 39 September 2012
15 and 35 nT
1138
2307
nT
Bx
By
Bz
UTC


Reeve Observatory 149.957W, 61.199N 08.10.2012
Figure 5(e) ~ 8 October 2012, 21 nT
0515
nT
Bx
By
Bz
UTC

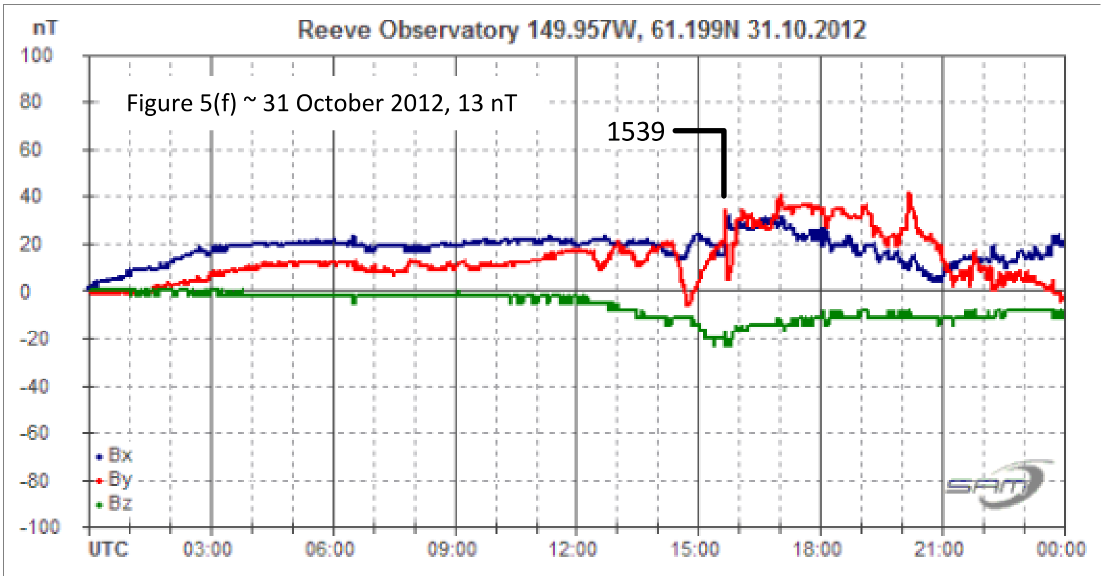

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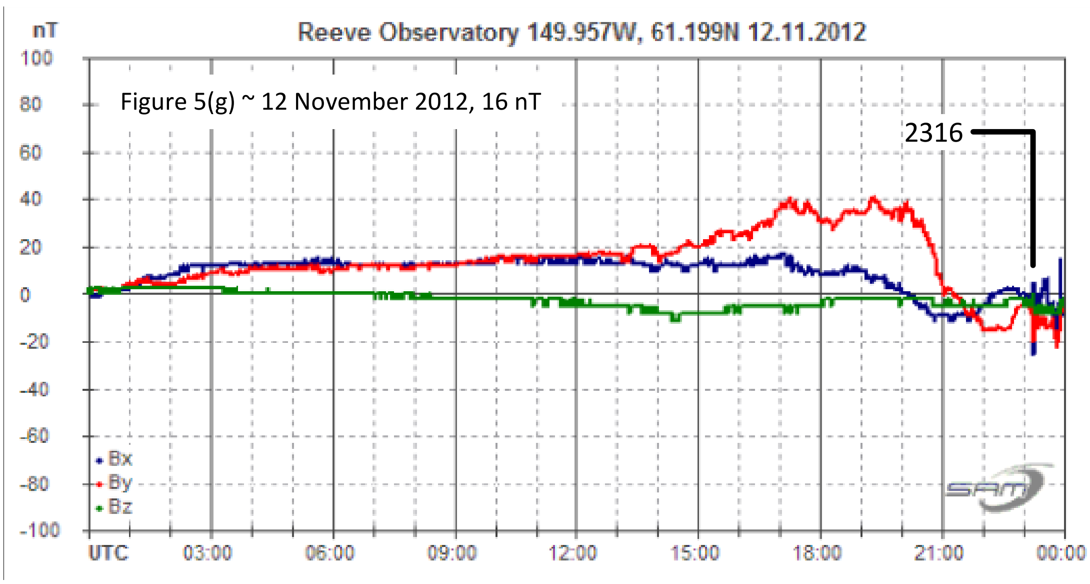
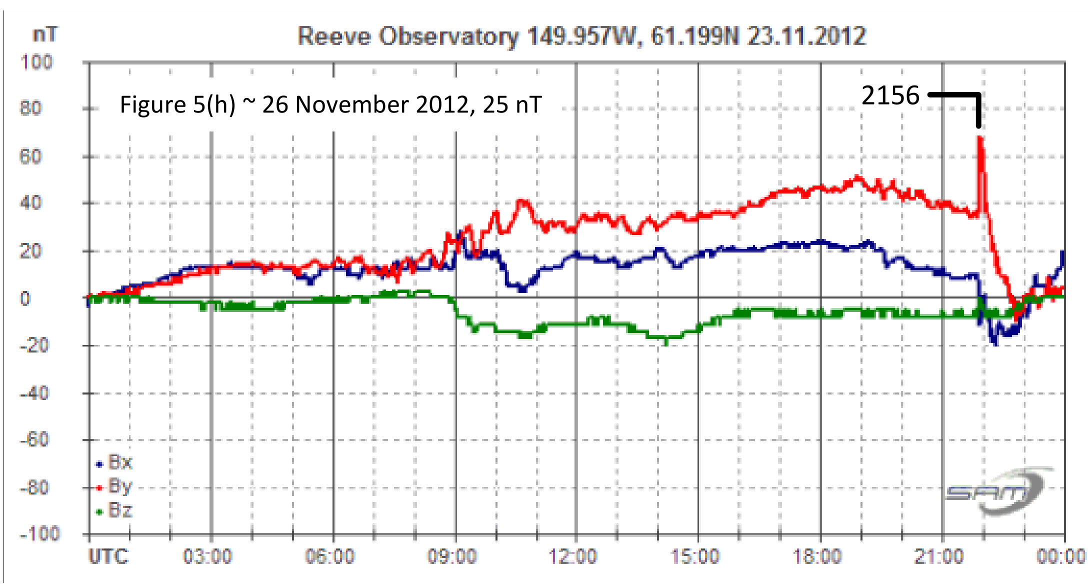
Figure 5(f) ~ 31 October 2012, 13 nT
1539
nT
100
80
60
40
20
0
-20
-40
-60
-80
-100
Bx
By
Bz
UTC
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00


Reeve Observatory 149.957W, 61.199N 12.11.2012
Figure 5(g) ~ 12 November 2012, 16 nT
2316
nT
100
80
60
40
20
0
-20
-40
-60
-80
-100
Bx
By
Bz
UTC
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00


Reeve Observatory 149.957W, 61.199N 23.11.2012
Figure 5(h) ~ 26 November 2012, 25 nT
2156
nT
100
80
60
40
20
0
-20
-40
-60
-80
-100
Bx
By
Bz
UTC
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15:00
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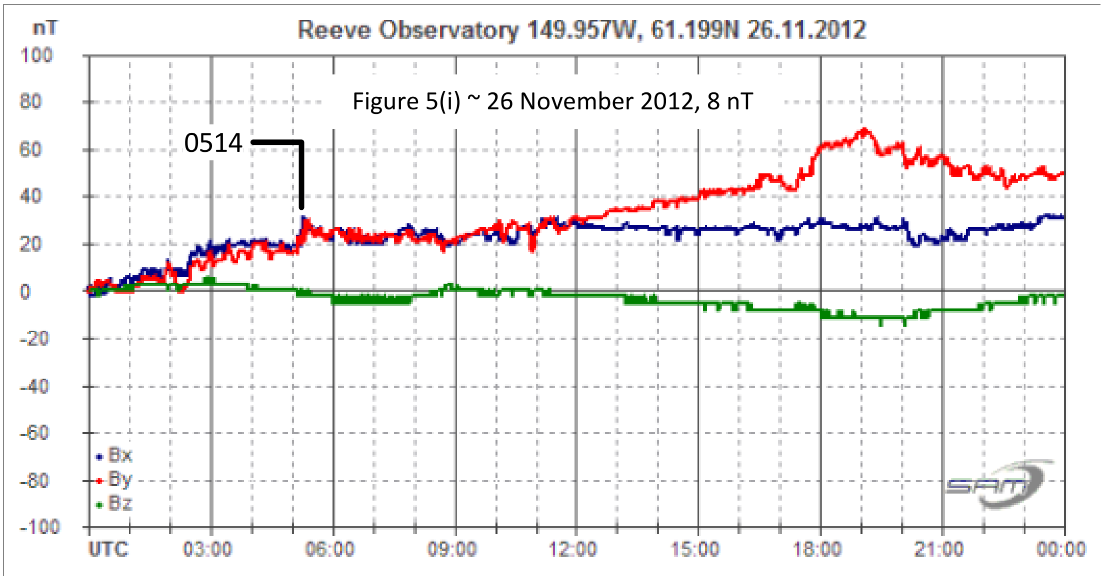
Reeve Observatory 149.957W, 61.199N 26.11.2012
nT
Figure 5(i) ~ 26 November 2012, 8 nT
0514
Bx
By
Bz
UTC
03:00
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12:00
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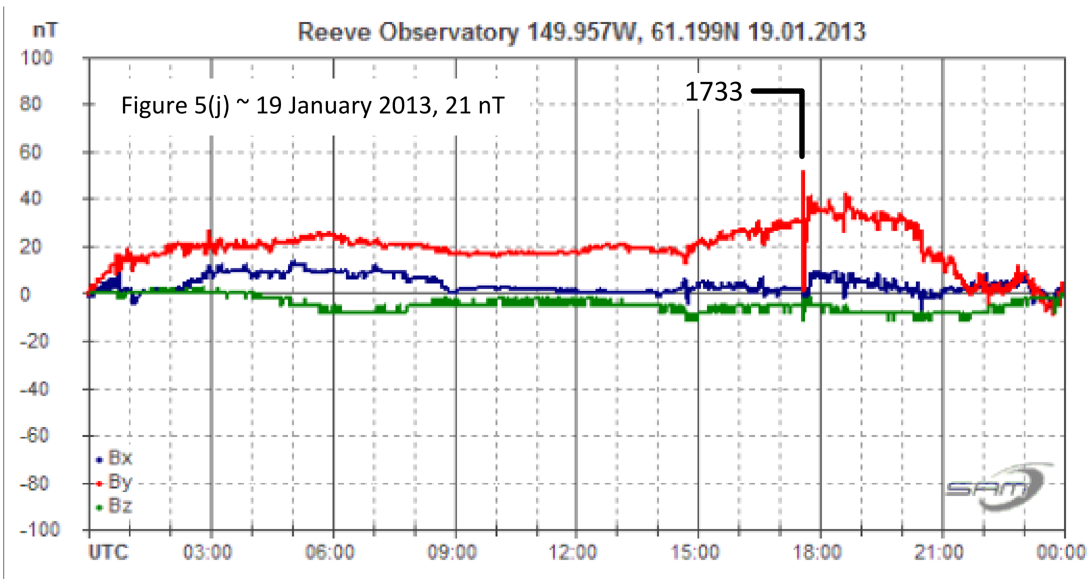
Reeve Observatory 149.957W, 61.199N 19.01.2013
nT
Figure 5(j) ~ 19 January 2013, 21 nT
1733
Bx
By
Bz
UTC
03:00
06:00
09:00
12:00
15:00
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21:00
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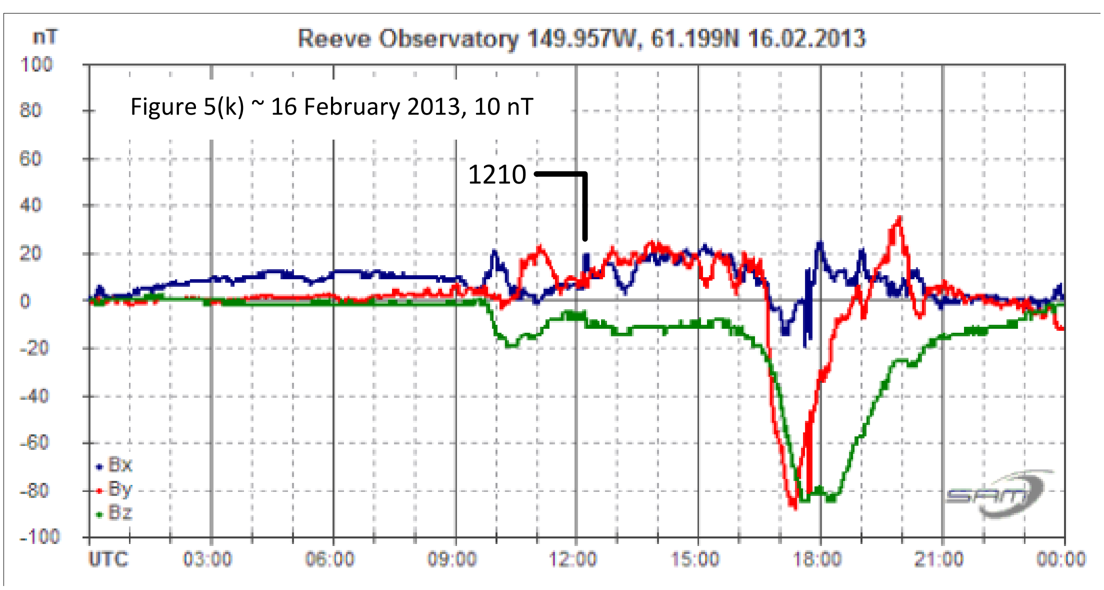
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nT
Figure 5(k) ~ 16 February 2013, 10 nT
1210
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By
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UTC
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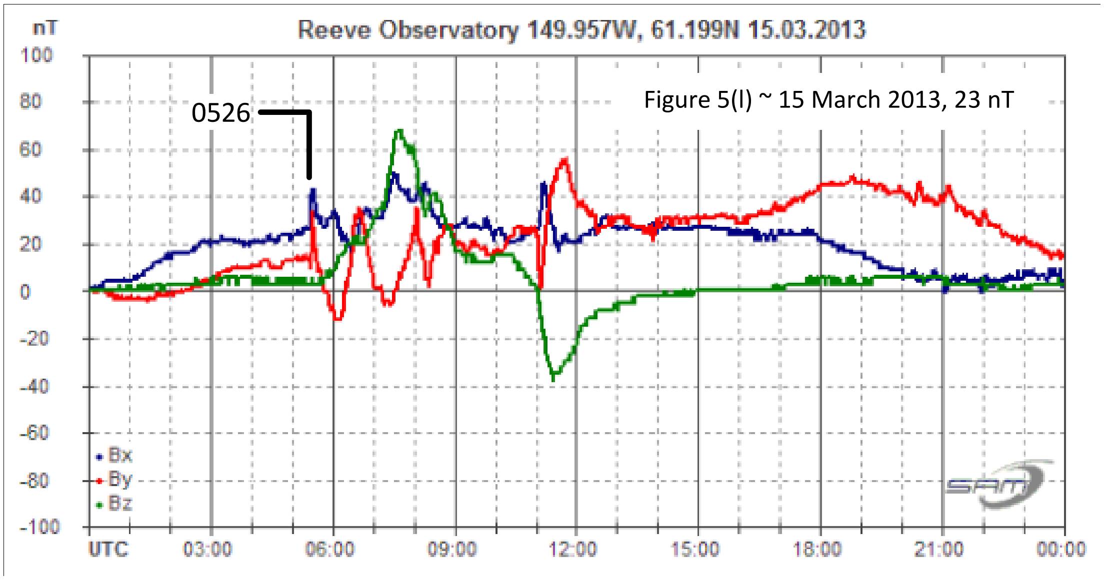
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Figure 5(l) ~ 15 March 2013, 23 nT
0526
nT
Bx
By
Bz
UTC 03:00 06:00 09:00 12:00 15:00 18:00 21:00 00:00

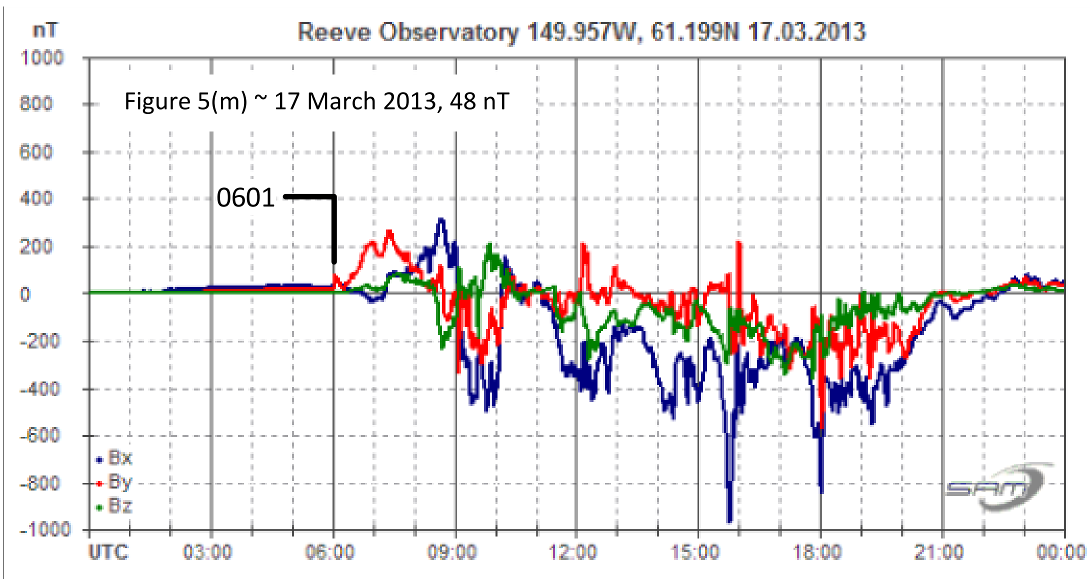
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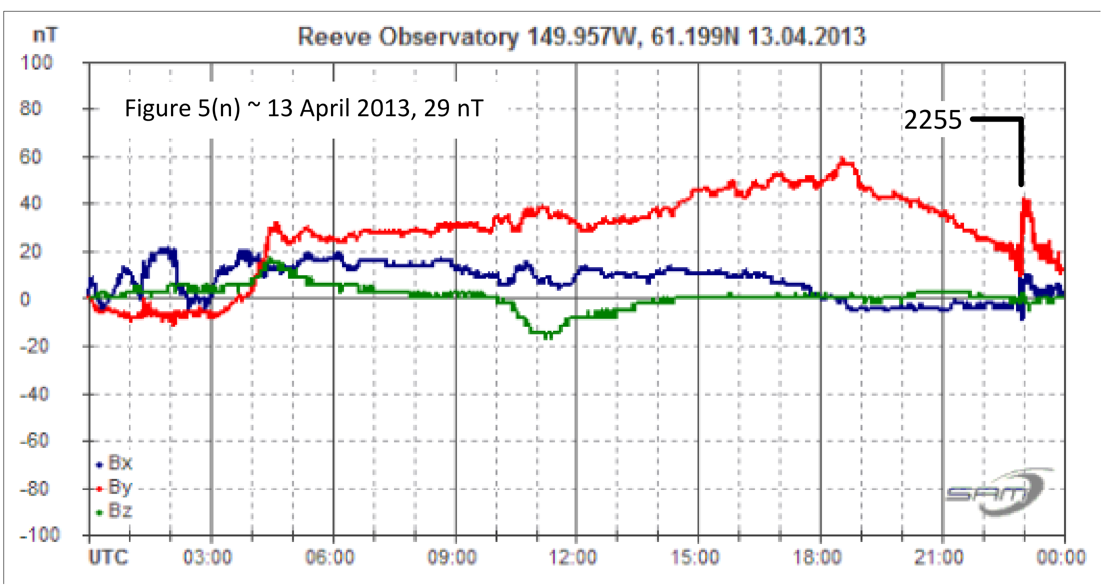
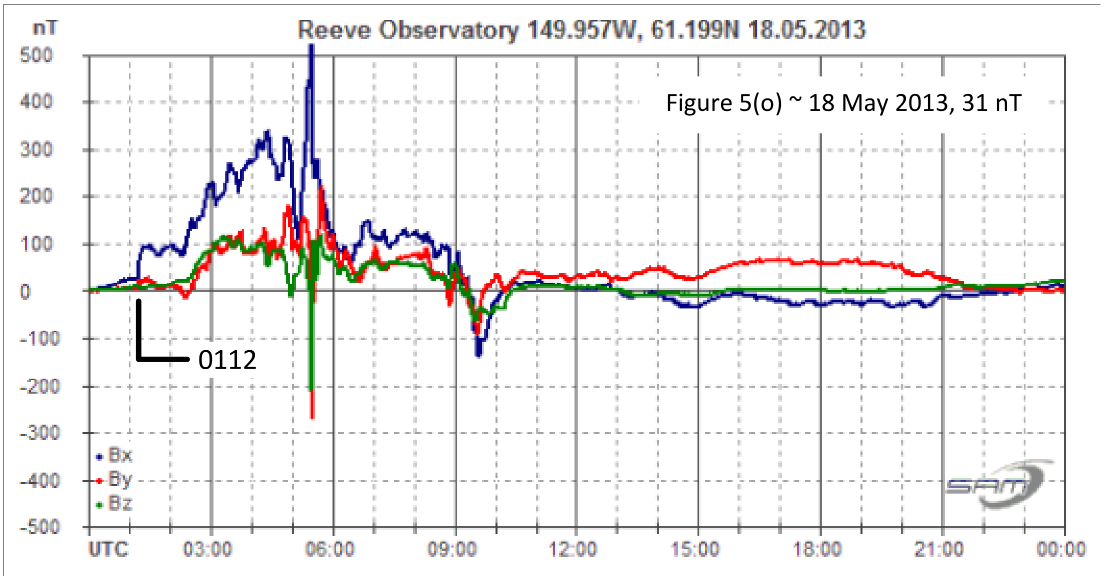
Figure 5(m) ~ 17 March 2013, 48 nT
0601
nT
Bx
By
Bz
UTC 03:00 06:00 09:00 12:00 15:00 18:00 21:00 00:00


Reeve Observatory 149.957W, 61.199N 13.04.2013
Figure 5(n) ~ 13 April 2013, 29 nT
2255
nT
Bx
By
Bz
UTC 03:00 06:00 09:00 12:00 15:00 18:00 21:00 00:00


Reeve Observatory 149.957W, 61.199N 18.05.2013
Figure 5(o) ~ 18 May 2013, 31 nT
0112
nT
500
400
300
200
100
0
-100
-200
-300
-400
-500
Bx
By
Bz
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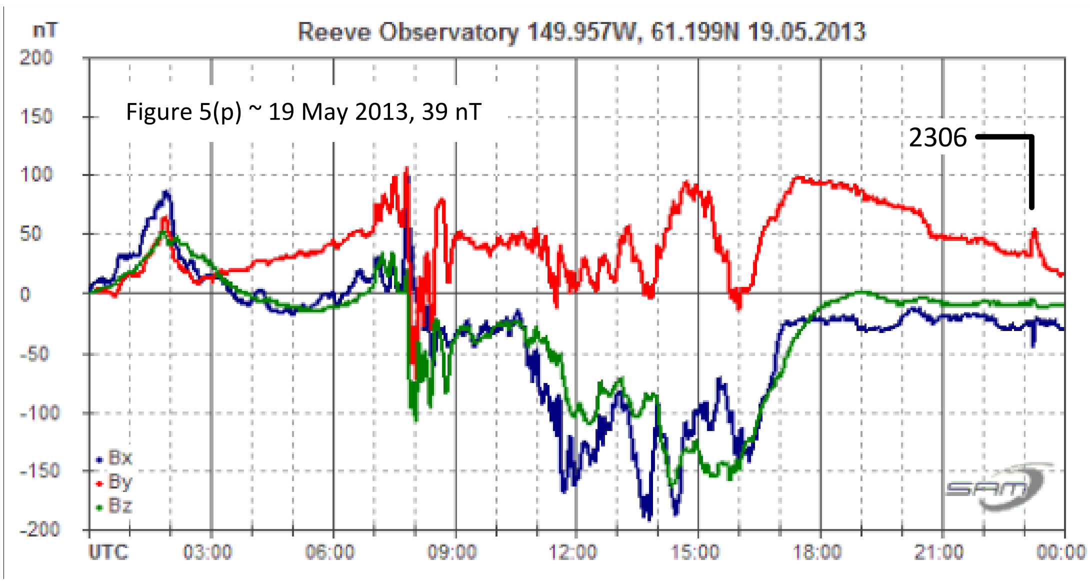
Reeve Observatory 149.957W, 61.199N 19.05.2013
Figure 5(p) ~ 19 May 2013, 39 nT
2306
nT
200
150
100
50
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-100
-150
-200
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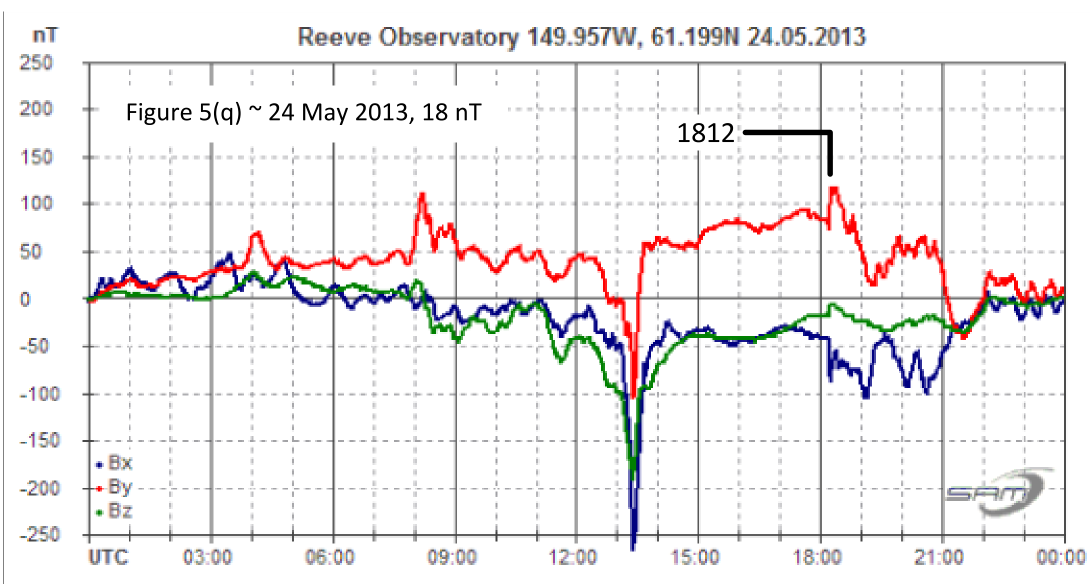
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Figure 5(q) ~ 24 May 2013, 18 nT
1812
nT
250
200
150
100
50
0
-50
-100
-150
-200
-250
Bx
By
Bz
UTC
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00

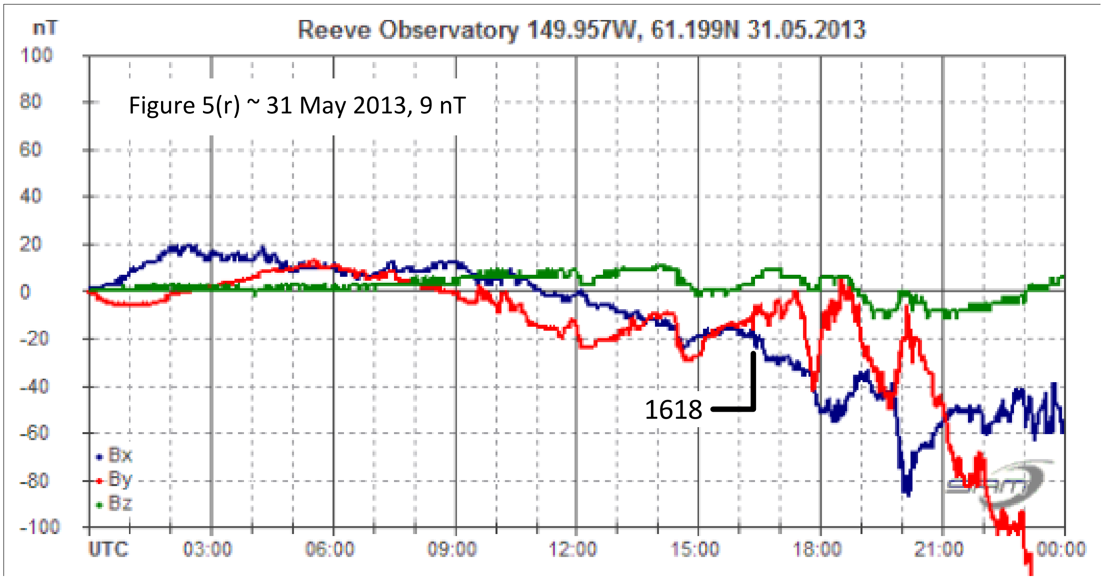


Figure 5 ~ Magnetograms for all sudden impulses observed at Anchorage, Alaska from 1 June 2012 to 1 June 2013

5. Sudden Impulse Plots

Data with 10 second resolution for nine of the observed sudden impulses were plotted over a 20 minute interval and are shown side-by-side with Sun elevation plots (figure 6). The pulses show wide variations in shape, rise time, duration and fall time. Some impulses are inverted and many show a slight dip just before the fast rise. The change in amplitude for some impulses is sustained for the plotted 15 minute post-impulse interval (and may last longer) but others return almost immediately to the pre-impulse level.

The impulse plots are of the horizontal component of the magnetic field, which is the vector sum calculated from the measured values of the X- and Y-components:

$$H = \sqrt{X^2 + Y^2}$$

where

H Horizontal component (nT)

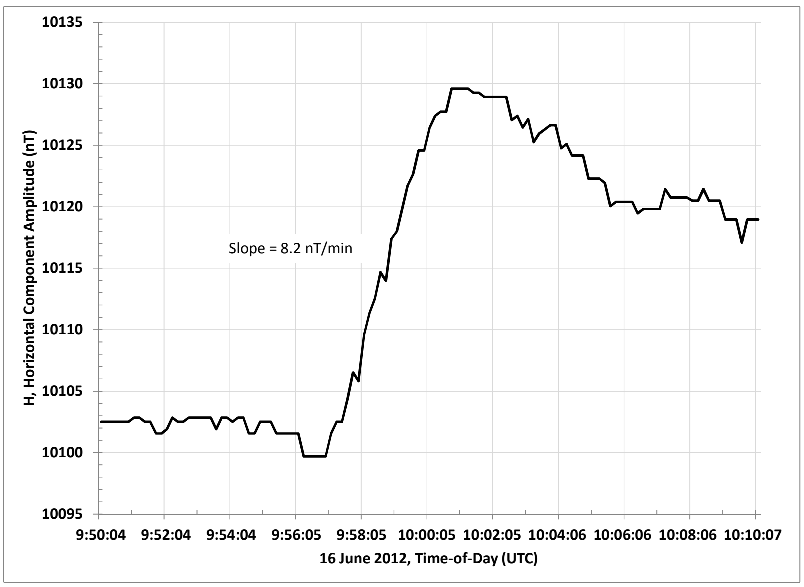
X North-south measurement (nT)

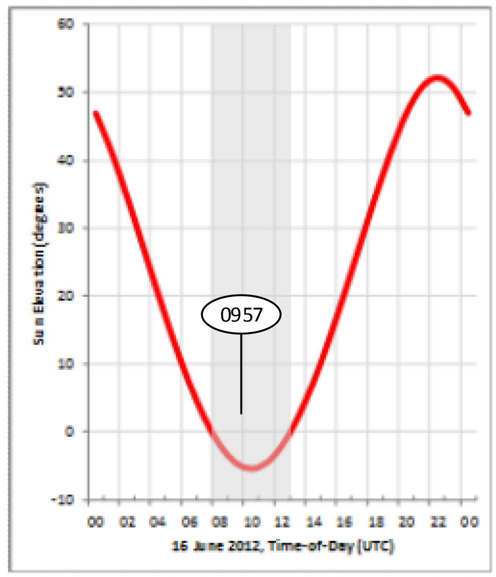
Y East-west measurement (nT)

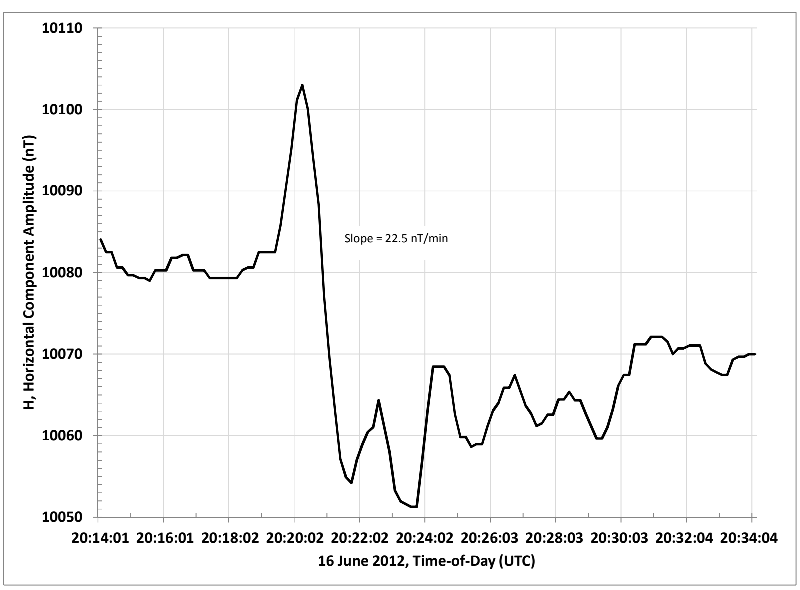
I suspected that the shape of the sudden impulses measured at a given location might be different for day and night conditions because the magnetosphere has considerably different shape on the sunlit side of Earth than on the night side (for example, see http://en.wikipedia.org/wiki/Magnetosphere). With that in mind, I also plotted the Sun elevation and annotated the time of each impulse.

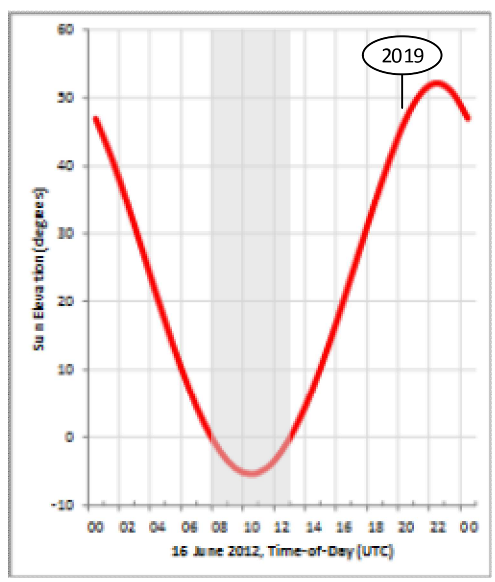
The Sun elevation plots are shaded to indicate the time when the Sun is below the horizon (that is, the observatory is on the night side of Earth). Although I plotted only nine of the twenty-one sudden impulses in this manner, the shapes do seem to be affected. For example, the impulse on 16 June 2012 (0957), 15 March 2013 and 17 March occurred on the night side and seem to have similar shapes. All others, except 19 January 2013, occurred on the daylight side, and they have similar shapes. However, I think the sample size is too small to draw any conclusions and that further study is needed. It also will be necessary to define what "similar shape" means.

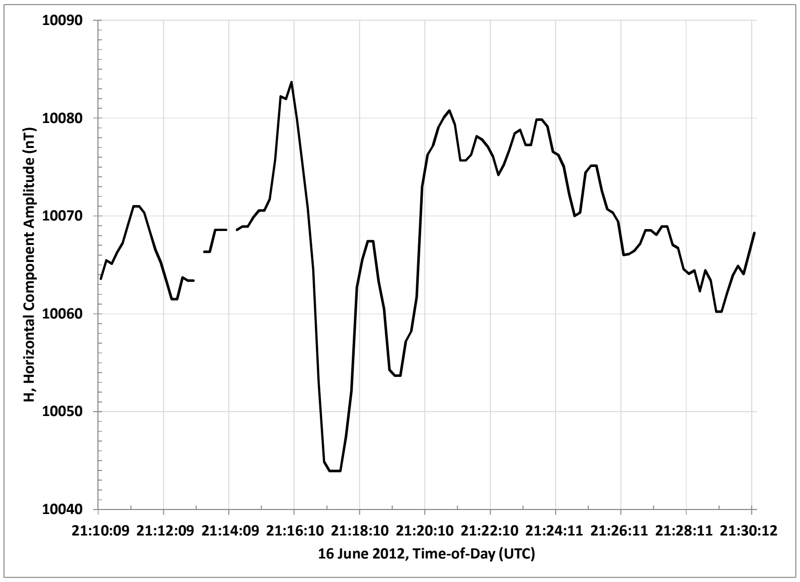
In response to my inquiry to Space Weather Prediction Center on 2 June 2013, SWPC provided the following (paraphrased) information on how they identify a sudden impulse: *Space Weather Prediction Center continuously monitors solar wind data from the ACE spacecraft looking for an interplanetary shock to pass. Usually a sudden impulse follows within the hour. During this time SWPC examines 1-minute resolution text data from the Boulder magnetometer looking for "a sudden perturbation, positive or negative, of several nT, in the H-component of the data".* When a sudden impulse is identified SWPC reports its amplitude and time as an Alert (see: http://www.swpc.noaa.gov/alerts/archive/current_month.html). Based on visual examination of the magnetograms, my measurements at Anchorage show good agreement with the reported SWPC impulse amplitudes.

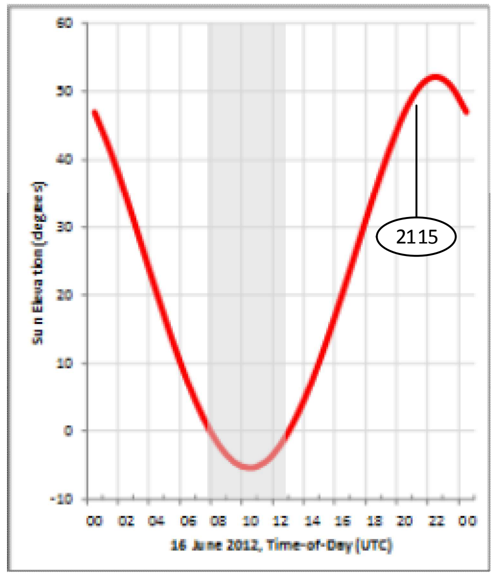


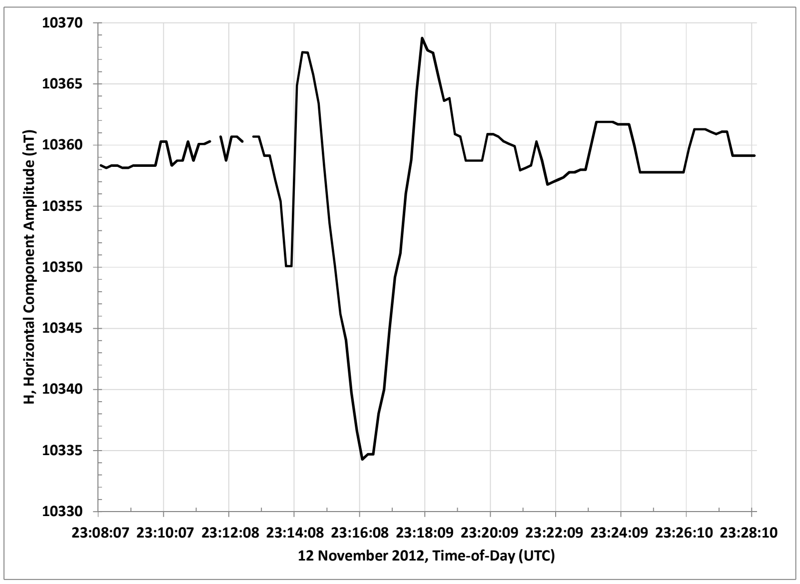


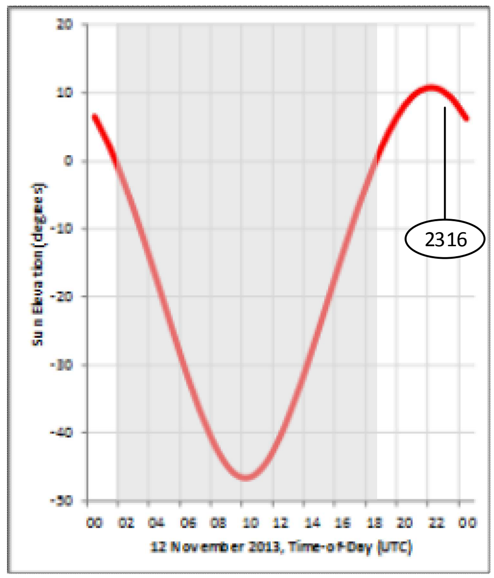





10090
10080
10070
10060
10050
10040
H, Horizontal Component Amplitude (nT)
21:10:09 21:12:09 21:14:09 21:16:10 21:18:10 21:20:10 21:22:10 21:24:11 21:26:11 21:28:11 21:30:12
16 June 2012, Time-of-Day (UTC)


Sun Elevation (degrees)
2115
00 02 04 06 08 10 12 14 16 18 20 22 00
16 June 2012, Time-of-Day (UTC)


10370
10365
10360
10355
10350
10345
10340
10335
10330
H, Horizontal Component Amplitude (nT)
23:08:07 23:10:07 23:12:08 23:14:08 23:16:08 23:18:09 23:20:09 23:22:09 23:24:09 23:26:10 23:28:10
12 November 2012, Time-of-Day (UTC)


Sun Elevation (degrees)
2316
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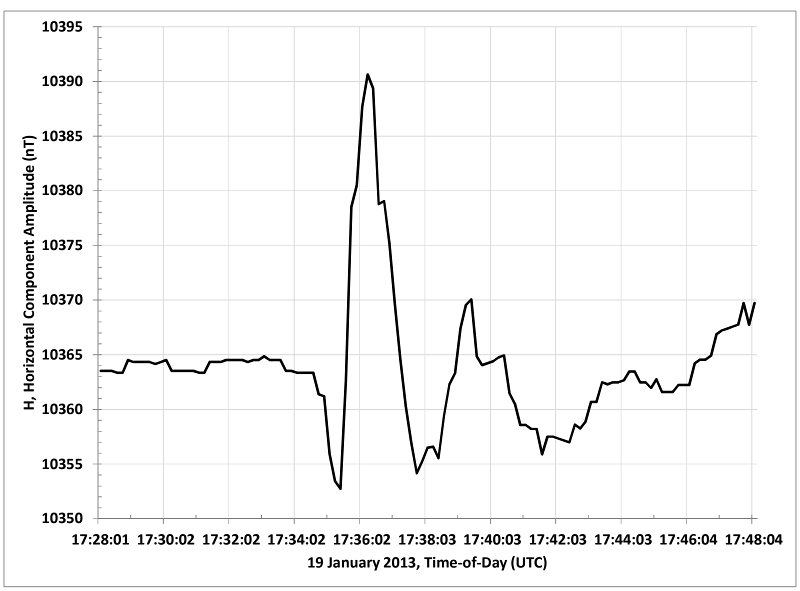
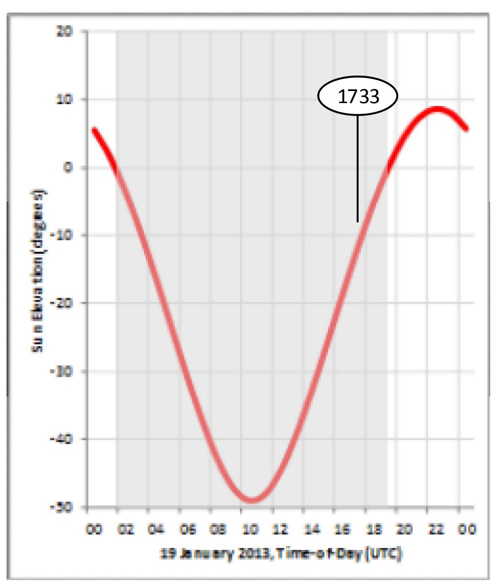
12 November 2013, Time-of-Day (UTC)


10395
10390
10385
10380
10375
10370
10365
10360
10355
10350
H, Horizontal Component Amplitude (nT)
17:28:01 17:30:02 17:32:02 17:34:02 17:36:02 17:38:03 17:40:03 17:42:03 17:44:03 17:46:04 17:48:04
19 January 2013, Time-of-Day (UTC)


Sun Elevation (degrees)
1733
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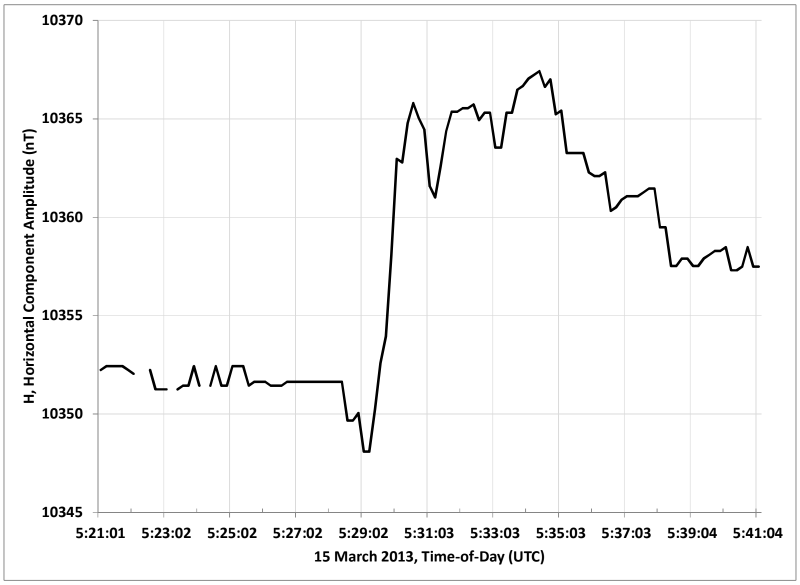
19 January 2013, Time-of-Day (UTC)


10370
10365
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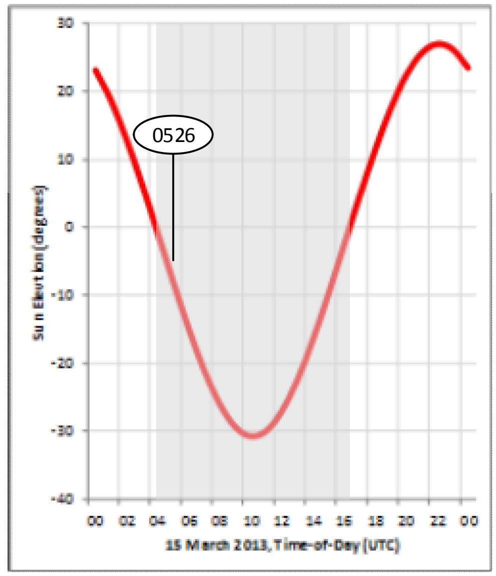
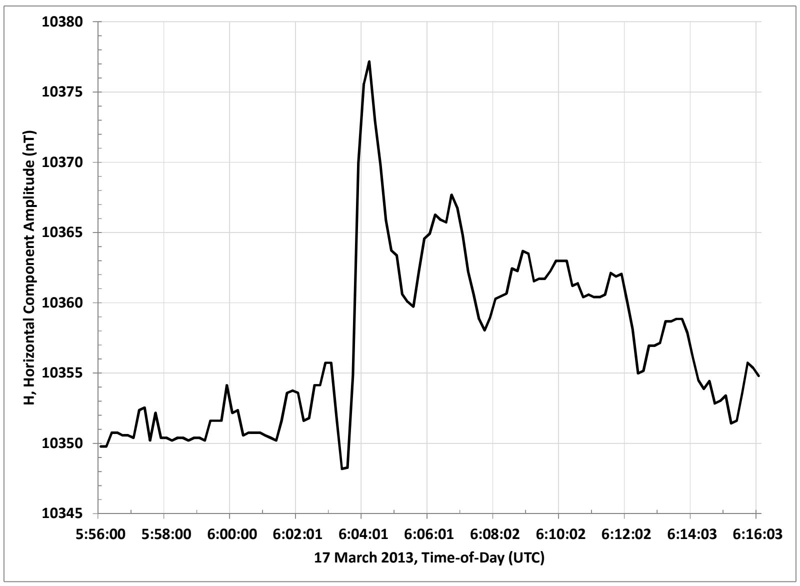
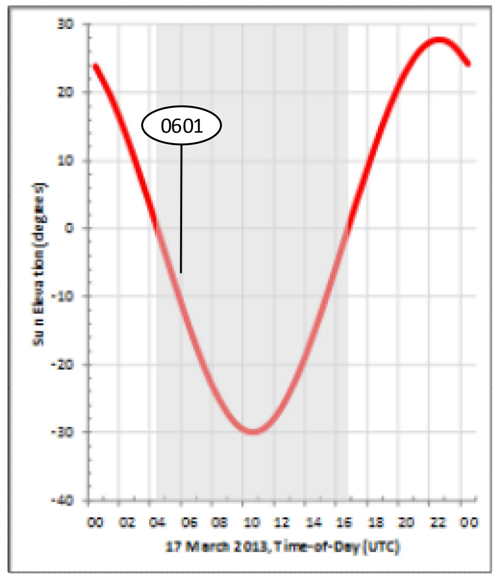
10355
10350
10345
H, Horizontal Component Amplitude (nT)
5:21:01 5:23:02 5:25:02 5:27:02 5:29:02 5:31:03 5:33:03 5:35:03 5:37:03 5:39:04 5:41:04
15 March 2013, Time-of-Day (UTC)


0526
30 20 10 0 -10 -20 -30 -40
00 02 04 06 08 10 12 14 16 18 20 22 00
15 March 2013, Time-of-Day (UTC)


10380
10375
10370
10365
10360
10355
10350
10345
H, Horizontal Component Amplitude (nT)
5:56:00 5:58:00 6:00:00 6:02:01 6:04:01 6:06:01 6:08:02 6:10:02 6:12:02 6:14:03 6:16:03
17 March 2013, Time-of-Day (UTC)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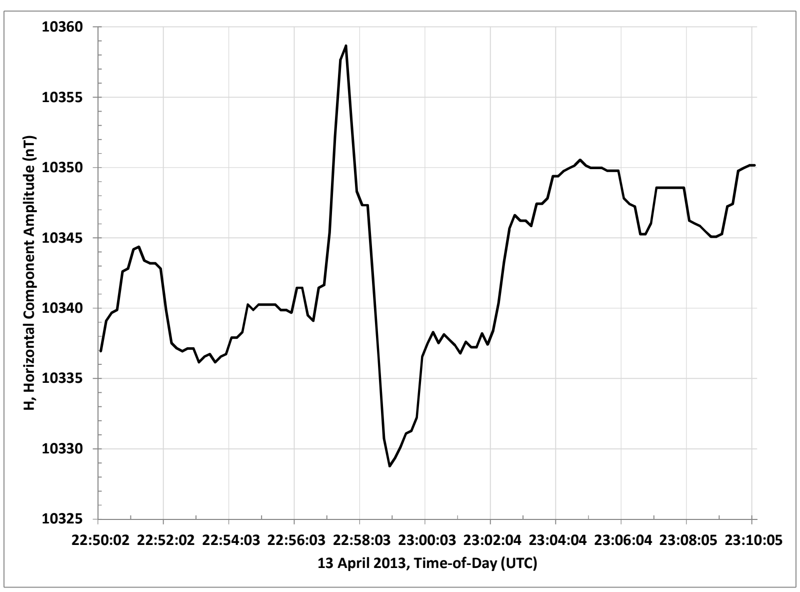
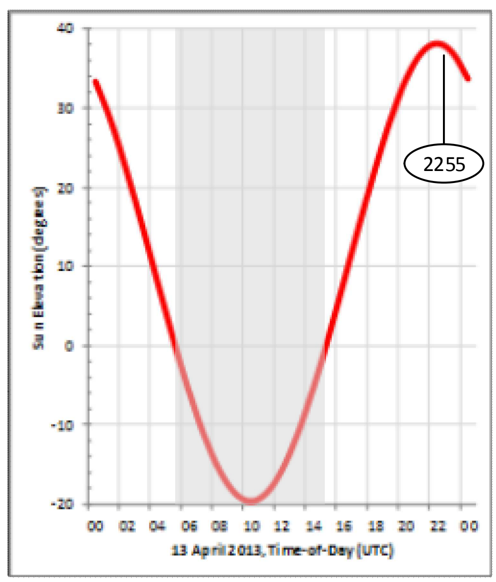

10360
10355
10350
10345
10340
10335
10330
10325
H, Horizontal Component Amplitude (nT)
22:50:02 22:52:02 22:54:03 22:56:03 22:58:03 23:00:03 23:02:04 23:04:04 23:06:04 23:08:05 23:10:05
13 April 2013, Time-of-Day (UTC)


2255
40 30 20 10 0 -10 -20
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13 April 2013, Time-of-Day (UTC)

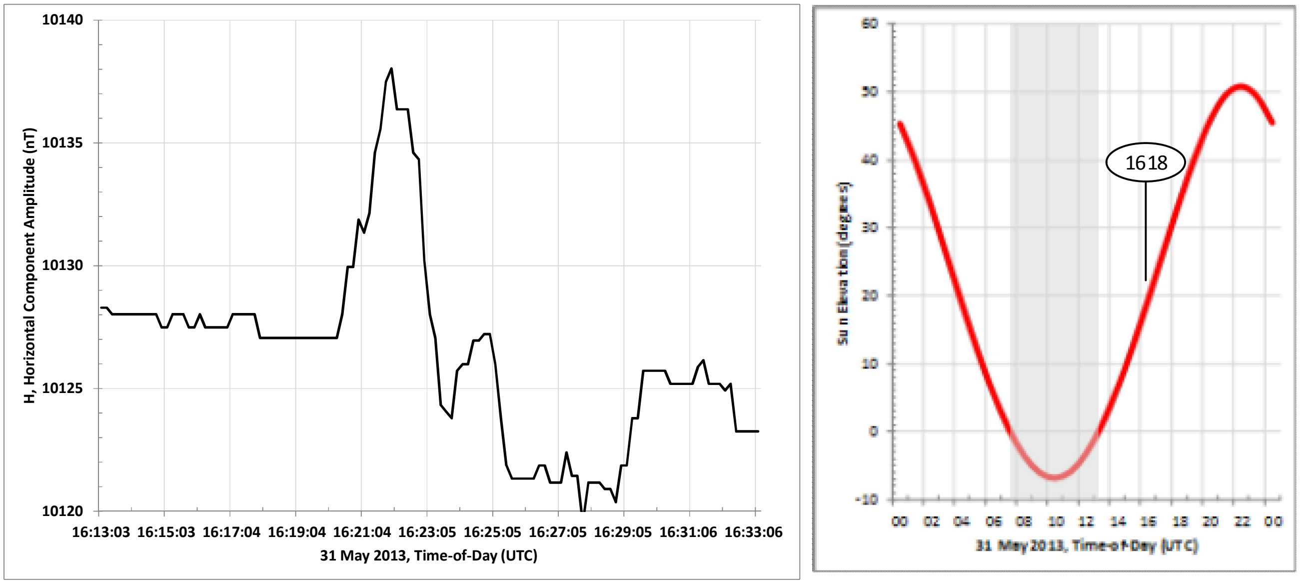

Figure 6 ~ Plots of nine sudden impulses (dates are given in the time axis label) along with the Sun elevation in degrees above or below the local horizon. Hours of darkness are shaded. All impulse plots span a 20 minute interval, approximately 5 minutes before and 15 minutes after the impulse.

6. Conclusions

The SAM-III geomagnetometer system at Anchorage, Alaska provides data that is comparable to professional magnetometers. Impulse amplitudes and shapes were examined in the context of the 24 hour magnetograms and detailed 20 minute plots with 10 second resolution. Statistics of the twenty-one impulses during the one year period indicate a 6:1 amplitude range of 8 to 48 nT, average of 24 nT, 1σ variation of 10 nT, and a wide range of impulse shapes (amplitude variations over time). The average CME speed was 654 km/s with 1σ variation of 118 km/s.

7. References and Further Reading

[Knipp] Knipp, D., Understanding Space Weather and the Physics Behind It, McGraw-Hill Book Co., 2011

[Reeve] Reeve, W., Geomagnetism Tutorial, 2011 (http://www.reeve.com/Documents/SAM/GeomagnetismTutorial.pdf)

8. Images Used in This Article

The SAM_View software captures the raw data sent by the SAM-III to the logging PC over its serial data interface. The raw data is saved as *.txt files. This data file was then imported into Excel, H calculated for the X- and Y-components, and the 20-minute time period around the impulse was plotted. The Excel chart was then copied/pasted into this document using the Picture (Enhanced Metafile) format.

The magnetogram images were saved from plots of the *.sam data files produced by the SAM_VIEW software. The *.sam data files differ from the raw data in that the data has been normalized (the original data files are not changed in any way). The images were then copied/pasted into Visio for annotation and copied/pasted into this document using the Picture (Enhanced Metafile) format.

The Sun elevation was calculated for the 24 hour period using the Multiyear Interactive Computer Almanac (MICA), http://aa.usno.navy.mil/software/mica/micainfo.php, imported as text data into Excel and plotted and formatted. The plots were then copied/pasted into Visio for annotation and shading and finally copied/pasted into this document using the Picture (Enhanced Metafile) format.