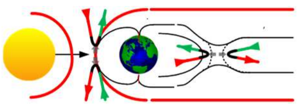
Time Aspects of the 12 October 2021 Geomagnetic Sudden Impulse

Whitham D. Reeve

1. Introduction



A geomagnetic *sudden impulse* (SI) is caused by the impact of a coronal mass ejection (CME) with Earth's magnetosphere. The impact suddenly compresses the magnetosphere and alters the ionospheric current systems, which, in turn, alter the magnetic field measured on the ground. Depending on the orientation of its embedded magnetic field and other factors, the CME may or may not produce a geomagnetic storm. If it produces a storm, the impulse often is called (after the fact) a *storm sudden commencement* (SSC) rather than a Sudden Impulse. If a storm does occur, it may start almost immediately after the CME arrives or sometime later. For purposes of this article, I will refer to the event of 12 October as a sudden impulse.

The question naturally arises about the timing aspects of sudden impulses measured by ground magnetometers around the world: Does a given SI register on all magnetometers at the same time – the *simultaneity hypothesis* – or is there a varying delay that depends on location – the *propagation hypothesis*? This is a tricky question because it is first necessary to define what constitutes the beginning of a sudden impulse. There also is the problem of interpreting magnetic field data, which could be affected by the impulse shape (waveform) at the location of the observation and the response, sampling rate and timing accuracy of the magnetometer at that location.

Attempts at answering the question of simultaneity or propagation have a long history. A conclusion drawn in 1933 after long and dedicated studies was that a given sudden impulse would occur "almost simultaneously on the Earth" {HGSS21}. Just exactly what does "almost simultaneously" mean? The referenced study does not provide an answer. In the 1966 book *Electromagnetism and the Earth's Interior*, the author states "The time of the outbreak of an SSC is simultaneous over the earth within an accuracy of 1 minute" [Rikitake]. Out of curiosity, the question is investigated here based on measurements at four widely separated ground locations using SAM-III magnetometers.

Throughout solar cycle 24 from December 2008 to December 2019 and during the early stages of solar cycle 25, many sudden impulses were observed and recorded by the SAM-III magnetometer at Anchorage, Alaska and reported {ReeveWeb}. A detailed investigation of sudden impulses from 1 June 2012 to 1 June 2013 observed at Anchorage discussed waveforms and other characteristics {Reeve13}. An article in mid-2021 compared the time of a sudden impulse on 12 May that was recorded both at Anchorage and Isle of Mull in Scotland {Reeve21}. The current article compares the sudden impulse times for the 12 October event observed at four stations including those at Anchorage and Isle of Mull.

2. Event description

An M1.6 solar flare on 9 October produced a CME that intercepted Earth on 12 October. The resulting sudden impulse was reported by Space Weather Prediction Center to occur at 0230 UTC with an amplitude of 33 nT as measured at the Geomagnetic Observatory Wingst (WNG) in Germany {SWPC-1}. As discussed below, this event was observed at slightly different times and at different amplitudes at four ground magnetometers around the world.

The CME was modeled by the Space Weather Forecast Office (part of NOAA in the USA) in terms of plasma density and radial wind velocity using the 3-dimensional Wang-Sheeley-Arge-Enlil solar wind prediction model {WSA-Enlil}. One of the images from the model for 12 October shows what was predicted (figure 1). The model predicted an increase in solar wind speed at Earth from around 300 km s^{-1} to about 600 km s^{-1} as well as a spike in density as the CME enveloped the geomagnetosphere. According to the model, the CME was very large and did not simply graze the geomagnetosphere.

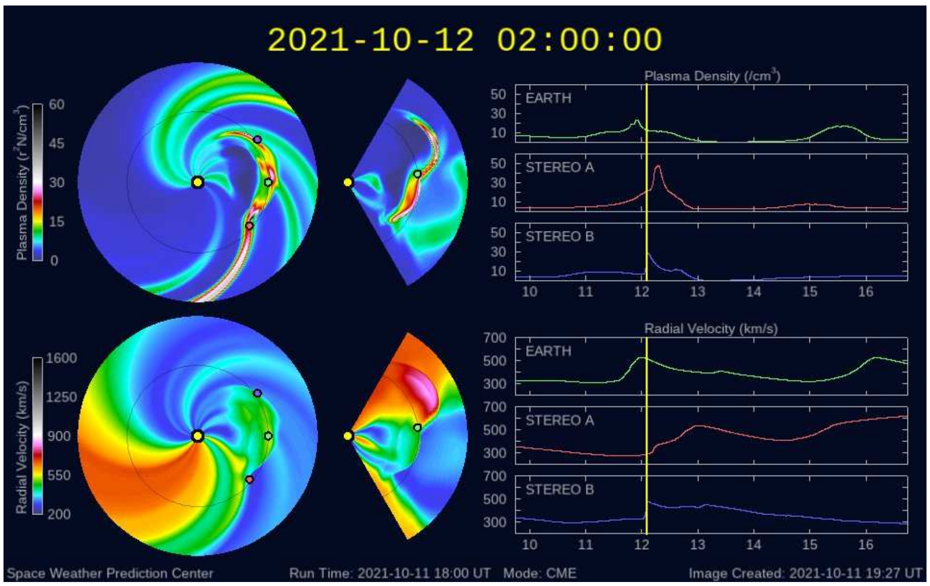


Figure 1 ~ The left circular images represent the Sun and Earth as viewed from above the ecliptic and the right pie-shaped images are viewed along the ecliptic. The Sun is in the center of the left circles and at the apex of the right pie-pieces. Earth is the small circle about 1/2-way to the right. The image shown here is the prediction for 0200, about 30 minutes before the actual CME impact. Note that the top images predicted a spike in the plasma density – CME impact – a few hours before the actual impact. Image source: {WSA-Enlil}

The SWPC *Forecast Discussion* report issued on 12 October at 0030, two hours before CME arrival, stated that updated modeling showed the CME speed to be about 900 km s^{-1} {SWPC-1}. The interplanetary (IP) shock passage was detected at the DSCOVR spacecraft (figure 2) at 0147 UTC on 12 October {SWPC-2}, and the sudden impulse was detected by the SAM-III magnetometers 40 min later at about 0227. The distance traveled from DSCOVR to Earth's magnetosphere is approximately 1.44 million km, so the actual CME speed was closer to 600 km s^{-1}.

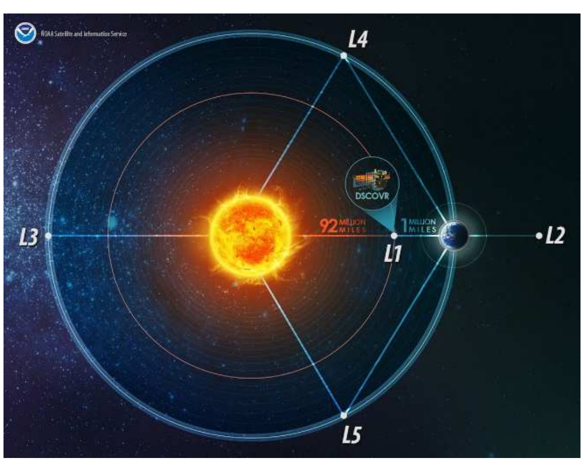


Figure 2 ~ View looking down on the ecliptic plane that shows the Lagrange points defined by the Sun-Earth system. The Deep Space Climate Observatory (DSCOVR) spacecraft is located at the L1 Lagrange point, 1.5 million km toward the Sun from Earth's center. The geomagnetosphere extends roughly 10 Earth radii toward the Sun, or around 64 thousand km. The spacecraft is a sentinel that provides approximately 15 to 60 min warning of coronal mass ejections, solar storms and other severe space weather headed toward Earth. Image source: {NASA}

Before CME impact, the geomagnetosphere already had been disturbed by enhanced solar winds and the auroral oval already had expanded and pushed the auroral electrojet to lower latitudes. It is noted that the auroral oval is considered to indicate the division between opened and closed geomagnetic field lines. Opened field lines reach outside the magnetosphere whereas closed field lines loop back to Earth within the magnetosphere. The auroral oval is represented by graphics on the University of Alaska – Geophysical Institute Aurora Forecasts webpage {Aurora}. On 11 and 12 October, the auroral oval easily covered Anchorage and its southern edge reached Isle of Mull (figure 3). The importance of the auroral oval is discussed in section 4.

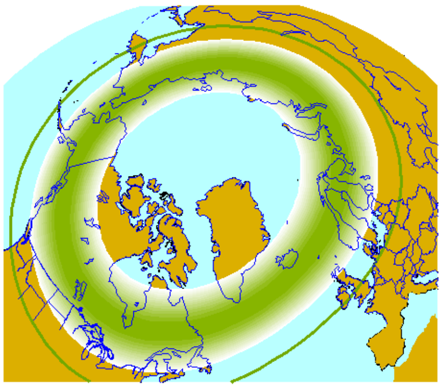


Figure 3 ~ The auroral oval, shown in this drawing as a green donut centered on the magnetic north pole, is for 11 October, the day before the CME impact. It was substantially the same on 12 October. The oval marks the region in which observations of the aurora have a high probability. It exists in both hemispheres and as a first approximation is fixed with respect to the Sun as Earth rotates below it. At solar midnight, the maximum of the auroral oval is centered about 67° latitude, but it extends to 77° at solar noon. Magnetic disturbances cause the oval to expand to both lower and higher latitudes. Image source: {Aurora}

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3. Observations

Data were obtained from four widely separated SAM-III magnetometer stations (table 1, figure 4) to examine the timing of the 12 October sudden impulse.

Table 1 ~ SAM-III magnetometer geographic and geomagnetic coordinates. See acknowledgements in section 6.

Station	**Geographic Coordinates**	**Geomagnetic Coordinates***	**Contact**
Anchorage, Alaska USA	61.199° N; 149.957° W	61.72° N; 94.50° W	Whitham D. Reeve
Isle of Mull Scotland	56.380° N; 6.001° W	58.85° N; 80.86° E	Roger Blackwell
Coonabarabran, New South Wales Australia	31.26° S; 149.22° E	37.82° S; 133.62° W	Michael Andre Phillips
Fort Collins, Colorado USA	40.502° N; 105.087° W	47.99° N; 37.65° W	Rodney Howe

* Coordinate transformation for 2021 using the IGRF-13 {Kyoto}

Differences in sudden impulse times and amplitudes were recorded by the four stations (table 2). Not shown in the table is the time reported by SWPC {SWPC-2}, which was 0230 UTC, about 3 min later than the four observations discussed here. SWPC reported an amplitude of 33 nT. The time difference may be due to the way SWPC interprets its data (see {Reeve13}). The differences in amplitude are due to the different geographic/geomagnetic locations of the magnetometers and, possibly, their sensitivities. The SAM-III magnetometer are operated as variometers with uncalibrated sensors.

The SAM-III magnetometer sensors at the four stations are oriented according to the Geographic Coordinate System and produce measurements at ground level for the X (north-south), Y (east-west) and Z (vertical) components. The data for the X- and Y-components are transformed to a Horizontal (H) component according to $H=\sqrt{X^2+Y^2}$.

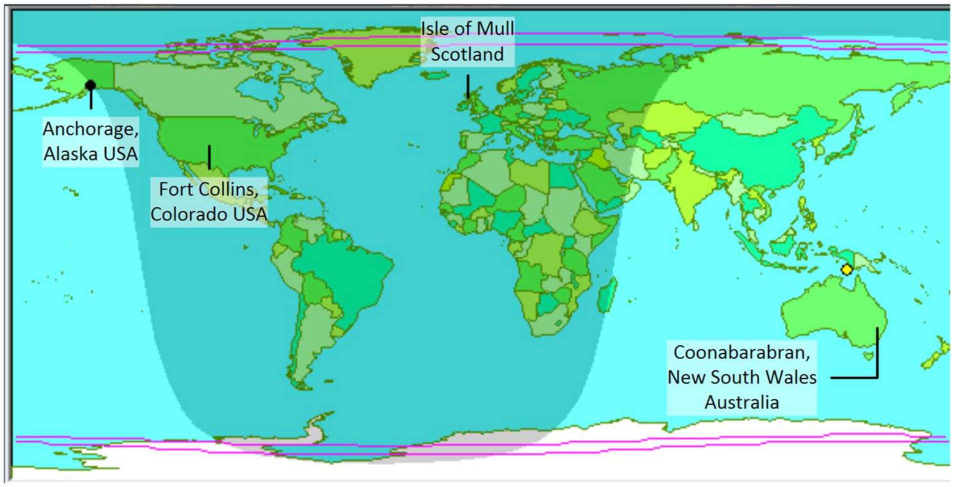

Figure 4 ~ Solar terminator at 0230 UTC on 12 October with marked station locations. The station locations with respect to the Sun were: Anchorage, Alaska USA – On sunset solar terminator; Isle of Mull, Scotland – Near solar midnight; Coonabarabran, New South Wales Australia – Near solar noon (see yellow circle, which represents the Sun); Fort Collins, Colorado USA – about 2 h after local sunset. Underlying image source: {DXViewer}

Table 2 ~ Sudden impulse (SI) observations and magnetometer sample rates. SI amplitudes are based on the H-component of the magnetic field as plotted below and are the differences between the knee (when the amplitude breaks and increases sharply) and the peak amplitude. SI Time is the time of the knee, which has about 10 s ambiguity.

Station (in order of occurrence)	**SI time (UTC)**	**SI amplitude (nT)**	**Sample rate (Hz)**
Isle of Mull Scotland	02:26:36	31	0.1
Fort Collins, Colorado USA	02:26:48	42	0.1
Coonabarabran, New South Wales Australia	02:26:56	30	0.1
Anchorage, Alaska USA	02:27:02	73	0.1
Averages	02:26:51	44	
Standard Deviations	10 s	17	

For comparison, the H-component at each station is normalized to the amplitude measured at 0215:00 UTC and then plotted together (figure 5). Also shown are Individual plots of the normalized H-component data from each station for the time period 0215 to 0245 UTC (figure 6). *Solar Local Time* (SLT) for each station is shown on a clock dial (figure 7) as well as given in the caption for the individual impulse plots. SLT indicates the relative position of the Sun without regard to local time. It is 00 in the anti-sunward direction (solar local midnight), 12 in the sunward direction (solar local noon) and 06 (dawn) and 18 (dusk) perpendicular to the sunward/anti-sunward line. SLT is similar to but not the same as *Magnetic Local Time*, which takes into account the local magnetic longitude and location of the magnetic north pole.

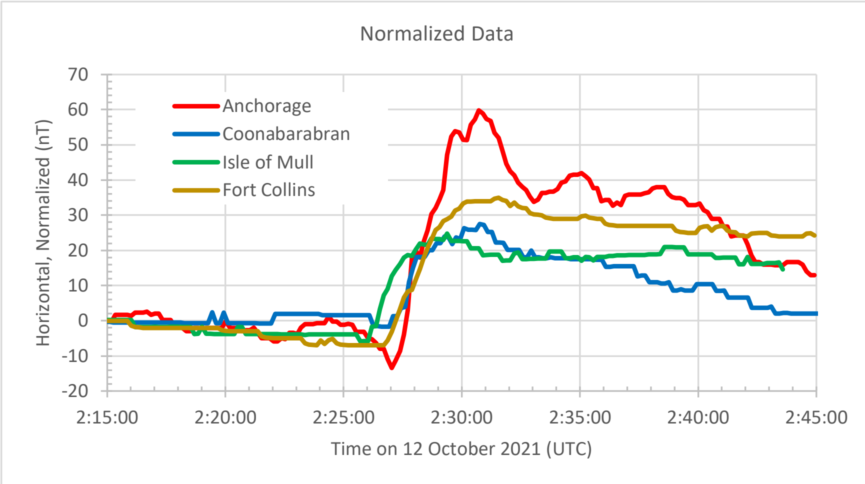

Figure 5 ~ Normalized H-component plots for the four stations. The X and Y data were first converted to H and then normalized to its value at 0215:00. Amplitudes are uncalibrated. Note that all stations recorded an amplitude dip immediately before the sharp increase.

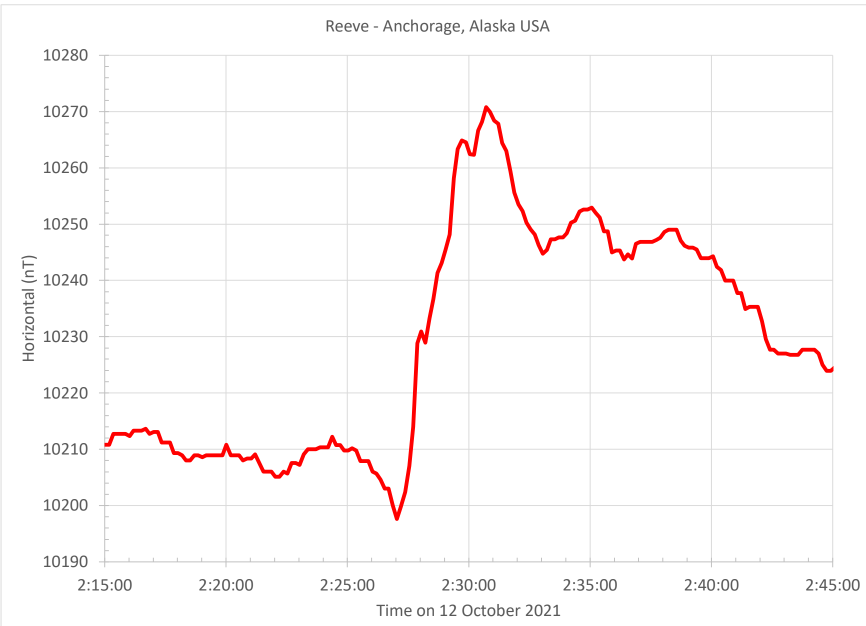

Figure 6.a ~ Raw H-component data plot for Anchorage, Alaska USA. The X and Y data were first converted to H and then normalized to its value at 0215:00. Amplitude is uncalibrated. Solar local time: 16.7 h.

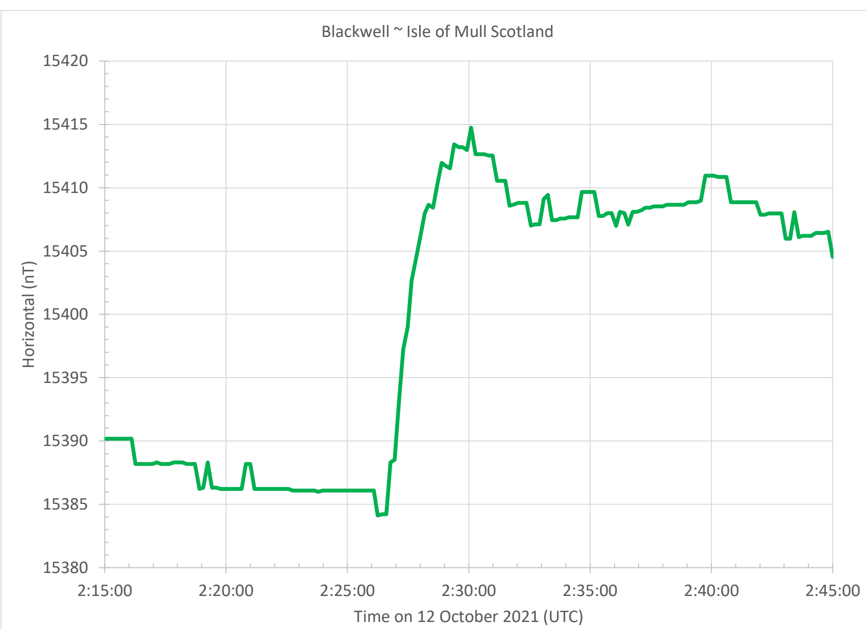

Figure 6.b ~ Raw H-component data plot for Isle of Mull Scotland. The X and Y data were first converted to H and then normalized to its value at 0215:00. Amplitude is uncalibrated. Solar local time: 02.3 h.

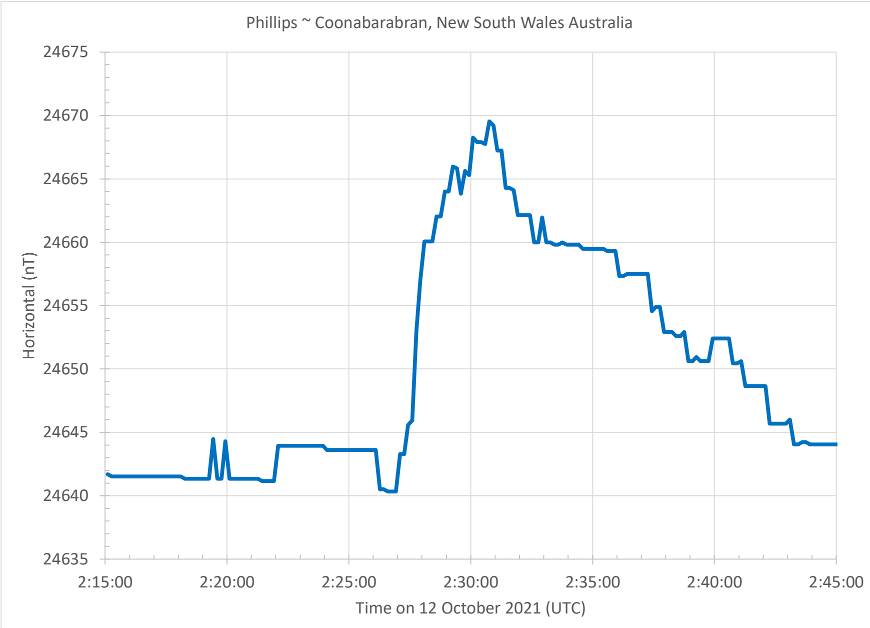

Figure 6.c ~ Raw H-component data plot for Coonabarabran, New South Wales Australia. The X and Y data were first converted to H and then normalized to its value at 0215:00. Amplitude is uncalibrated. Solar local time: 12.7 h. Magnetic local time: 12.7 h.

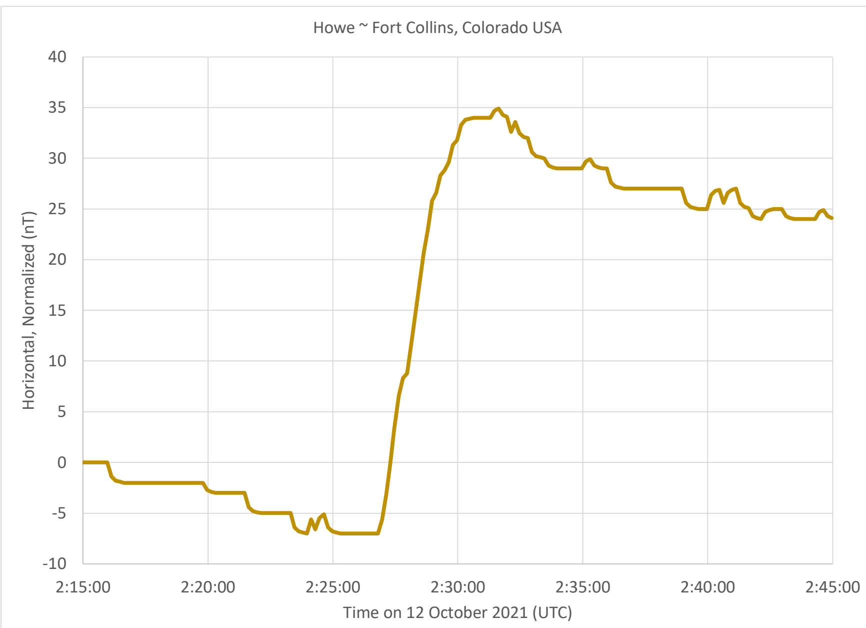

Figure 6.d ~ Normalized raw H-component data plot for Fort Collins, Colorado USA. The X and Y data were first converted to H and then renormalized to its value at 0215:00. Amplitude is uncalibrated. Solar local time: 19.7 h.

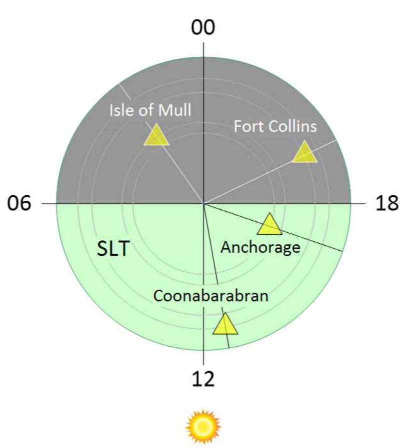

Figure 7 ~ Solar local time at each station when the sudden impulse occurred. SLT is based on the position of the Sun with respect to each station. Solar local noon 1200 is the Sun's transit and solar local midnight is 0000 and directly opposite noon SLT on the Sun-Earth line. This view is looking down on Earth from above the North Pole and shows the stations at their approximate magnetic latitudes.

4. Discussion

The purpose of this section is not to answer the question of simultaneity or propagation but to discuss possible natural effects that could explain the differences in times measured by the four ground magnetometers. The meaning of *almost simultaneously* mentioned in {HGSS21} cannot be answered by analyzing one event measured at four stations. Nevertheless, the sudden impulse event occurred within about 26 s at the four stations located on both the dayside and nightside of Earth. This could be considered *almost simultaneously*. It is noted that the actual time difference between the four stations could be more or less than 26 s because of the 10 s resolution of the SAM-III data.

It is interesting that the station near the midnight side of Earth, Isle of Mull in Scotland, registered the sudden impulse first. The station at Anchorage on the sunset solar terminator registered it last, 26 s after Scotland. A look at {Reeve21}, which compared sudden impulse times measured at Anchorage and Isle of Mull on 12 May 2021, shows that Anchorage detected the sudden impulse 29 s after Scotland, very close to the lag time measured on 12 October.

The estimated CME speed was 600 km s^{-1} when it impacted the magnetosphere (see section 2). At that speed, a 26 s delay implies a travel distance of 15 600 km, or about 2.5 Earth radii. Earth's magnetosphere extends about 8 to 10 Earth radii on the dayside and at least 100 radii on the nightside. However, if propagation delays are involved, the propagation was against the CME direction.

Electric fields exist in the high latitude ionospheres that drive electric currents aligned with the magnetic field lines (*field-aligned currents*). The magnetic field lines at high latitudes are quite steep. Horizontal currents (*Pederson currents*) flow to complete the electric circuit of the field-aligned currents. The electric field also drives another horizontal current system (*Hall current*) that flows across the polar cap from noon to midnight and then from midnight to noon along the auroral oval.

These horizontal current systems concentrate in the auroral oval and comprise the *auroral electrojet* (figure 7). The electrojet has a width of a few hundred kilometers, carries a few million amperes and is located in the evening-midnight-morning sector of the E-region ionosphere in the auroral zone [Reeve10]. It is thought there is only one electrojet but some evidence exists of two, one flowing westward from roughly morning (dawn) to midnight and another flowing eastward from roughly evening (dusk) to midnight. At the time of the CME impact, Isle of Mull was in the midnight region, Anchorage was in the evening (dusk) region, and Coonabarabran was in the noon region. Fort Collins was nearer to the evening region than the midnight region (see discussion of solar local time in section 3).

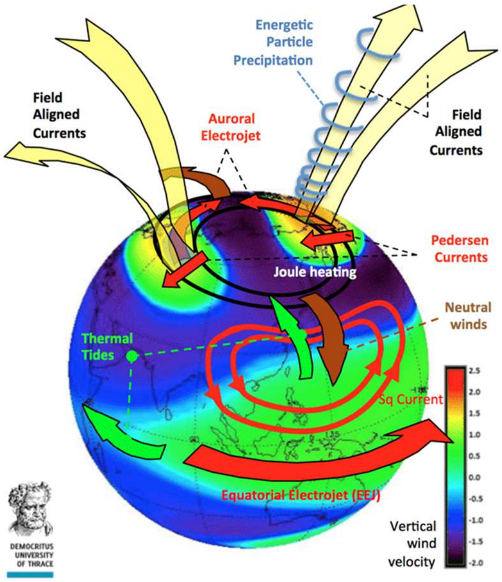

Figure 7 ~ Graphic showing the extreme complexity of the magnetospheric current systems including the auroral and equatorial electrojets and what are thought to be their drivers and interactions. These systems are disturbed by a CME impact and it is unlikely that this disturbance is symmetrical and equal at all ground locations where the SAM-III magnetometers are located. The current systems are weaker or stronger depending on the nightside or dayside and higher or lower latitudes. Image source: Source: {EGU}

As mentioned in section 2, the auroral oval was already expanded on early 12 October due to the enhanced solar wind. Coupling already existed between the magnetosphere and ionosphere at high magnetic latitudes. At the relatively high magnetic latitudes of Isle of Mull and Anchorage, 59° N and 62° N, respectively, the abrupt change in the electrojet current caused by the CME in turn caused an impulse in the magnetic fields in the vicinity of the electrojet. However, the fields and currents usually are not symmetrical around Earth, leading to effects that can vary with location. In this case, there was a delay involved in the effects observed at Anchorage compared to Isle of Mull.

The other two stations, Coonabarabran and Fort Collins, at 38° S and 48° N magnetic latitudes, respectively, are at comparatively lower latitudes and closer to the *equatorial electrojet*. This electrojet is produced by the electric field in the dayside ionosphere and drifts westward as the Sun moves across the sky. The equatorial electrojet is linked to the auroral electrojet by the field-aligned currents mentioned above.

Other situations could exist at the four stations that affect local magnetic measurements. These include remnant magnetism, proximity to the oceans, which have different conductivity than land masses, and underground geologic structures, such magnetic ore bodies, and other near-surface geomagnetic anomalies that distort the local magnetic field. The conductivity and current flows and the induced magnetic fields near Earth's surface are affected by all these characteristics. Rapidly varying ionospheric currents will induce rapidly varying magnetic fields that reinforce or oppose Earth's internal field. However, it is not known how these could affect the timing of abrupt magnetic impulses caused by CMEs.

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5. Instrumentation

The SAM-III magnetometer consists of a main controller and three sensors (figure 8). The typical SAM-III generally operates as a variometer in which changes in the magnetic field induction (and not its absolute value) are the important parameters. The four stations in this investigation are set to sample and store the magnetic field measured by each sensor at 10 s intervals (0.1 Hz rate).

The data produced by the SAM-III magnetometers at all stations discussed here are time-stamped by the PCs that collect the data. The real-time clocks in the PCs are synchronized by the Network Time Protocol (NTP) with GNSS-traceable time references. The data are sent from the SAM-III controller to the PC on an asynchronous EIA-232 serial link at 9600 b s^{-1}. Variations in the PCs and their operating systems result in slightly different time stamp sequences. For example, the Anchorage magnetometer produced a data point with a time stamp at 0215:01. The nearest time stamp for the Coonabarabran data was 0214:56 and for the Isle of Mull data was 0215:02, a maximum difference of 6 s. It is believed the time stamps on individual PCs are correct to better than 20 ms of Coordinated Universal Time (UTC).

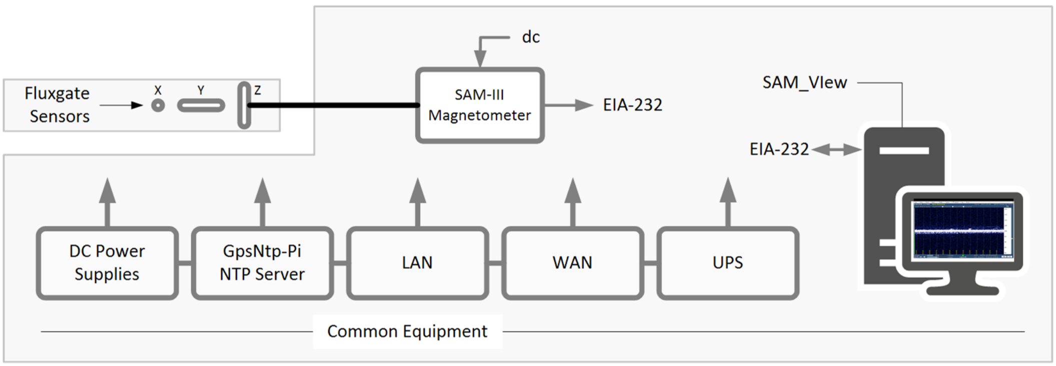

Figure 8 ~ System block diagram for the 3-axis SAM-III station at Anchorage including the common equipment shared across the observatory. The SAM-III sensors are buried about 1 m below the ground surface to reduce temperature effects. Not all stations have the same common equipment. Anchorage, Coonabarabran, and Isle of Mull are configured to measure all three axes, while Fort Collins is configured for two axes, X and Y. Image © 2021 W. Reeve

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6. Summary

Magnetic field measurements of the sudden impulse on 12 October 2021 at four widely separated SAM-III magnetometers showed a timing spread 26 s. It is believed that the time stamps at the four stations are accurate to better than 20 ms, but the relatively low data sample rate of 0.1 Hz leads to 10 s resolution of the data. In the context of {HGSS21}, the measurements show the sudden impulse registered at the four locations *almost simultaneously*.

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7. Acknowledgements

The author gratefully acknowledges the SAM-III data contributions by Michael Andre Phillips (Coonabarabran, New South Wales, Australia), Roger Blackwell (Isle of Mull, Scotland) and Rodney Howe (Fort Collins, Colorado, USA). The author also is grateful for review comments provided by Doğacan Su Öztürk of the University of Alaska Fairbanks – Geophysical Institute.

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8. Weblinks & References

{Aurora} https://www.gi.alaska.edu/monitors/aurora-forecast

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{Reeve21} Reeve, W. and Blackwell, R., Comparative Observations of the 12 May 2021 Geomagnetic Event, 2021, available at: https://www.reeve.com/Documents/Articles%20Papers/Observations/Reeve-Blackwell_CompObrv_12May2021%20GeomagEvnt.pdf

{ReeveWeb} https://www.reeve.com/RadioScience/Radio%20Astronomy%20Publications/Articles_Papers.htm#Geomagnetism_and_SAM-III

[Rikitake] Rikitake, T., Electromagnetism and the Earth's Interior, Elsevier Publishing Company, 1966 (part of the series *Developments in Solid Earth Geophysics*)

{SWPC-1} ftp://anonymous@ftp.swpc.noaa.gov/pub/forecasts/discussion/10120030forecast_discussion.txt

{SWPC-2} ftp://anonymous@ftp.swpc.noaa.gov/pub/forecasts/discussion/10130030forecast_discussion.txt

{WSA-Enlil} https://www.swpc.noaa.gov/products/wsa-enlil-solar-wind-prediction

Document Information

Author: Whitham D. Reeve

Revisions: 0.0 (Original draft started, 13 Nov 2021)
0.1 (Verified time data, 14 Nov 2021)
0.2 (Added current systems, 16 Nov 2021)
0.3 (Completed 1st draft, 21 Nov 2021)
0.4 (Added magnetic local times, 27 Nov 2021)
0.5 (Added [Rititake] reference, 01 Dec 2021)
0.6 (Distribution, 06 Dec 2021)

Word count: 3437

File size (bytes): 3086370