Geomagnetic Sudden Impulse Observations

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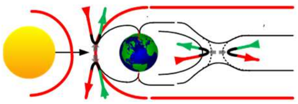

Sudden Impulses result from the impact of an Earth-directed coronal mass ejection (CME) on, and the rapid compression of, Earth's magnetosphere {Reeve13}. However, depending on the interplanetary magnetic field (IMF) direction and the plasma speed and density associated with the CME, the after-effects widely vary. CMEs are part of *space weather*, the overall effects on spacecraft and Earth's inhabitants by variations in solar activity. The persistently high level of solar activity during the first couple of weeks in September 2024, including an almost continuous stream of Earth-directed coronal mass ejections, provided plenty of bad space weather.

This article describes three Sudden Impulses during September that resulted in significantly different effects. Sudden Impulses are only part of a geomagnetic event and do not occur in isolation. What happens before and after are just as interesting and also discussed here. The times and intensities of the September Sudden Impulses are listed in table 1. The first impulse, on 4 September, was not followed by a significant disturbance to Earth's magnetic field but storm conditions followed the impulses on 12 and 16 September within 3 hours. Storm conditions are defined by a K-index ≥ K5 as measured by ground magnetometers. The three impulses were detected and recorded by the SAM-III magnetometers at Anchorage Radio Observatory and HAARP Radio Observatory (figure 1). The magnetometers are described later in terms of block diagrams.

Figure 1 ~ Map of Southcentral Alaska showing the locations of Anchorage Radio Observatory (left marker) and HAARP Radio Observatory (right). The great circle distance between the two, shown by the black line, is 286 km. HAARP is 2° farther north in magnetic latitude than Anchorage and 4° east in longitude.

Geomagnetic coordinates:
Anchorage: 61.72° N : 94.41° W (2022)
HAARP: 63.62° N : 90.42° W (2024)

Note: Geomagnetic coordinates change over time because of the wandering nature of Earth's internal dipole field.

Image source: http://www.movable-type.co.uk/scripts/latlong.html

Coronal mass ejections: A CME can consist of a billions ton of charged matter, mostly protons, electrons and helium nuclei, blasted away from an active region in the Sun's corona by magnetic instabilities. The CME is a plasma cloud. It is highly conductive and, consequently, the Sun's magnetic field is frozen in and carried along with it. As the CME moves away from the Sun to the surrounding solar system, the embedded solar magnetic field is called the *Interplanetary Magnetic Field*.

CMEs can travel at speeds above 2000 km s^{-1} and, if Earth-directed, can reach Earth in less than 1 day but most CMEs are much slower and require around 2 to 3 days to reach Earth. A CME may overtake or fall behind the ambient solar wind, coronal hole high-speed streams or other CMEs, further complicating their effects on Earth's magnetosphere. After leaving the Sun, CMEs spread out in an expanding cloud, so only a fraction of a typical Earth-directed CME actually intercepts Earth's magnetosphere.

Table 1 ~ Summary of Sudden Impulses on 4, 12 and 16 September 2024. The Shock Times are from SWPC reports of the measurements at ACE or DSCOVR spacecrafts. The Impulse Times also are from SWPC reports for the Boulder USA (4 and 16 September) and Canberra AU (12 September) ground magnetometers. The Sudden Impulse Amplitudes are from the Anchorage / HAARP observatories and are estimated from graphical Bx and By data that are added vectorially to find the horizontal amplitude.

Date (2024)	**Type**	**Shock time (UTC)**	**Impulse time (UTC)**	**Amplitude (nT)**	**Remarks**
4 September	SI	0940	1030	56 / 58	Amplitude 40 nT at Boulder
12 September	SSC	0254	0350	76 / 90	Amplitude 32 nT at Canberra
16 September	SSC	2249	2329	63 / 120	Amplitude 39 nT at Boulder

Not all CMEs are Earth-directed and sometimes only the flanks of a CME interact with Earth's magnetosphere and cause transient effects or disturbances. These interactions may last for days. Because CME speed and density are important parameters in space weather forecasting, NOAA uses spacecraft measurements to model CMEs for alert and warning purposes (figure 2). The modeling is not yet perfect but is under continuous improvement. For example, the plasma density and speed associated with the 16 September impulse were predicted to peak at 1300 but actually occurred about 10 hours later. Note that, according to the model for 16 September, a good part of the CME was predicted to miss Earth.

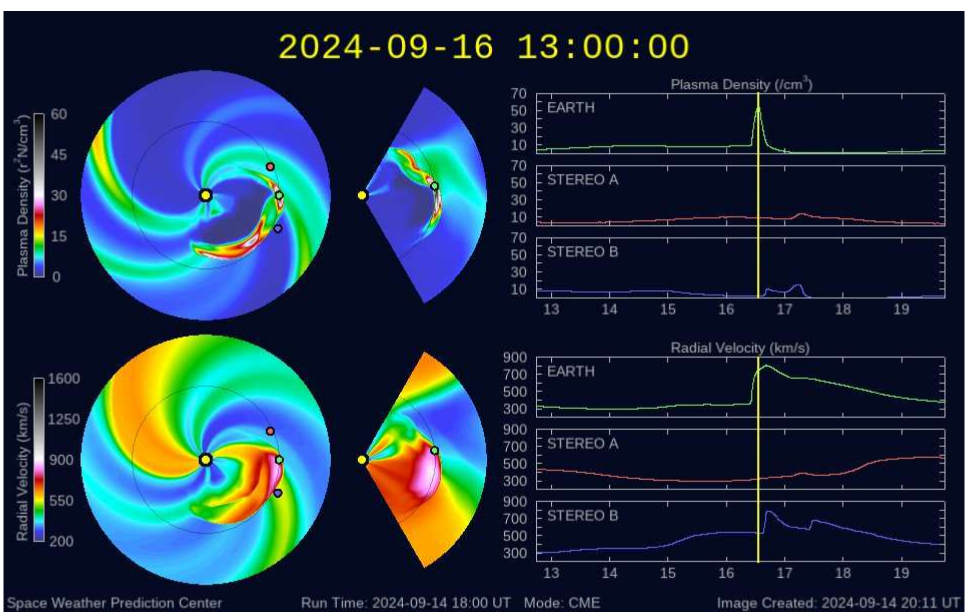

Figure 2 ~ WSA-ENIL model of the 16 September CME showing predicted arrival at Earth (yellow cursor). In this case, the predicted time was early by about 10 hours. The actual arrival time at Earth was 2329. The circles at left depict density (upper) and wind speed (lower) from an overhead view. The pies depict the same properties from an orbital plane view. Earth is the middle of three dots to right of the Sun at center. Image source: https://www.ngdc.noaa.gov/enlil/

<u>Interplanetary magnetic field</u>: The IMF component aligned with Earth's magnetic dipole field has great importance in space weather. It and other properties are measured by the ACE and DSCOVR sentinel spacecrafts located about 1.5 million km from Earth along the Sun-Earth line. The IMF component that is aligned with Earth's dipole field is labeled Bz. This is not to be confused with the component of Earth's magnetic field also labeled Bz but measured by ground magnetometers. The terrestrial Bz points from Earth's surface to its center.

If the IMF Bz component is opposite in polarity to Earth's magnetic field, that is, the Bz component is southward or negative, the two fields can easily merge and a geomagnetic storm will follow almost immediately if the IMF remains southward for roughly an hour or more. The storm typically is stronger the longer the southward component persists and the higher its amplitude. On the other hand, if the IMF Bz component has the same polarity as the geomagnetic field (northward or positive), little or no merging takes place and a storm is unlikely to follow.

If a storm follows almost immediately, the impulse more accurately is called a Sudden Storm Commencement (SSC) rather than Sudden Impulse (SI). However, in this article, the Space Weather Prediction Center's (SWPC) simplified terminology will be used wherein both types of impulses are labeled Sudden Impulses. SWPC provides near-real-time warnings and alerts of space weather phenomena, and it is not known at the first sign of an impulse whether a storm follows or not.

An IMF and geomagnetic field merging event generally follows a sequence called the *Dungey Cycle*, which is described in the following numbered narrative keyed to figure 3 (Reeve21}:

1. When the interplanetary magnetic field embedded in the solar wind has a southward component, opposite to Earth's magnetic field, the two fields merge on the dayside of the magnetosphere in a process called *magnetic reconnection*;
2. The formerly closed geomagnetic field lines facing the Sun open as they merge with the IMF. The IMF and magnetosphere are now linked and solar wind plasma can enter the magnetosphere at high latitudes;
3. The open field lines are carried over the Earth's poles by the solar wind. The field lines are stretched out on Earth's nightside in the region called the *magnetotail*;
4. As they stretch out, the open-field lines move toward the center plane of the tail where they reconnect again, closing the magnetic flux that was opened on the dayside. The time from 1 to 4 is on the order of 1 hour;
5. Part of the magnetic flux moves down-tail away from Earth, but part of the flux returns by internal flows to their origin;
6. This process carries plasma resident in the magnetotail toward Earth;
7. The highly energized electrons in the plasma are trapped by the magnetic field and are further energized when they arrive within a few Earth radii by voltage variations along the magnetic field lines. The cycle may repeat in a quasi-periodic process called a *substorm* with a period of roughly 1 to 3 hours. If the IMF is northward, it is deflected around Earth and there is no reconnection.

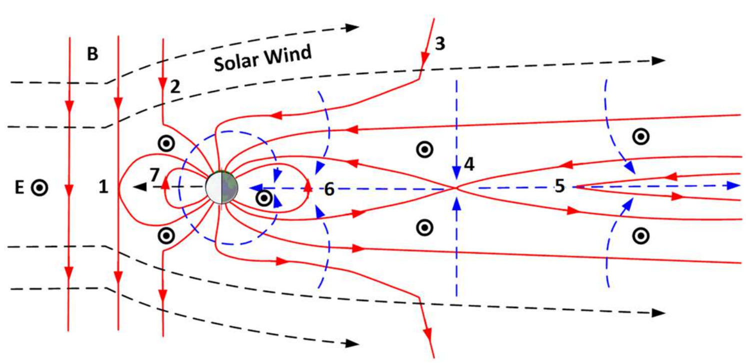

Figure 3 ~ Conceptual drawing of magnetic merging and reconnection called the Dungey Cycle. The numbers indicate the sequence described in the text. The Sun is to the left out of view, and the solar wind is shown by the black dashed lines flowing left-to-right. The magnetic field (B) is shown in red; the IMF is southward. Earth is the circle with the sunlit side facing the Sun and has a northward magnetic field. Current flow (E) is into the page shown by the circled dots. Magnetic flux movement is shown by blue arrows. Diagram adapted from: [Seki]

Spacecraft data: Data plots from the ACE or DSCOVR spacecrafts are shown in this section. Note that the time spans shown by these plots are 1 or more days and are chosen to aid the discussion of events that may span several days. The plots have been annotated to clarify dates and times of the events described, and a black vertical arrow has been added to indicate the time of the CME shock at the spacecraft. Each image contain numerous graphs and traces and those relevant to the discussion are (from top):

1st graph: Bt (black trace) and Bz (red trace) which are the total IMF and IMF component aligned with Earth's dipole field, respectively. The ambient Bt near Earth (1 AU) is on the order of 5 to 8 nT and values above 10 nT can be considered to be elevated. Shocks are usually indicated by a step-change in Bt whereas Bz can change more slowly or more erratically. A shock observed at the spacecraft will not be observed in terrestrial magnetic field data until the CME has traveled from the spacecraft to Earth's magnetosphere; the travel time depends on the speed but is on the order of 40 to 60 minutes.;

3th graph: Solar wind density (orange trace). The ambient solar wind density at 1 AU is on the order of 3 particles cm^{-3}. CMEs typically raise the density while coronal hole high-speed streams (CHHS) lower it;

4th graph: Solar wind speed (magenta trace). The ambient solar wind speed is on the order of 350 to 450 km s^{-1} and elevated values may be due to a CME or CHHS. Speeds associated with CMEs vary widely and usually are slower near Earth than when they are ejected from the Sun's corona.

It was mentioned above that a geomagnetic storm did not follow the Sudden Impulse on 4 September. The traces for Bt and Bz received from the ACE spacecraft have been circled. Examination of data shows that the IMF Bz component (red trace, figure 4) is positive for most of the period after the CME shock passage was observed there at 0940. The density and speed measurements indicate the solar wind remained near background levels although they both appear slightly elevated compared to the pre-shock time.

In the case, of the 12 September impulse event, which was followed by a geomagnetic storm, the ACE data shows a sustained negative Bz component not only for the day of the impulse but for a few days afterwards (figure 5). Geomagnetic storms persisted throughout this period. The ACE plots include other interesting information, which is described in the captions. The situation was similar on 16 September (figure 6) in which the Bz component was negative for two days afterwards. The ACE data clearly shows when the CME shock passed the spacecraft – see the step increase in the black trace in the graph near the top of the data plots, which corresponds very closely to the time the Bz component, shown by the red trace, turned negative.

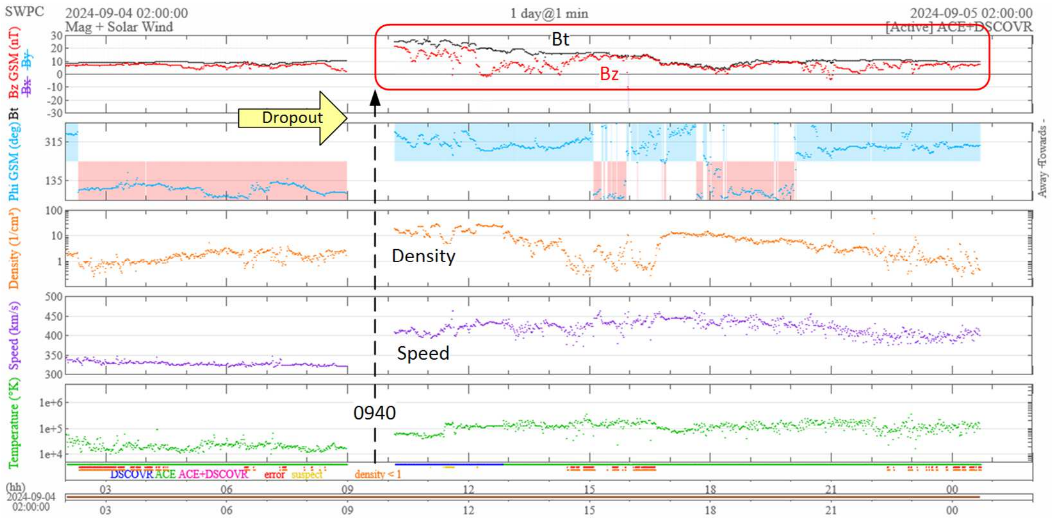

Figure 4 ~ ACE + DSCOVR spacecraft solar wind data for 4 September. The shock, measured by Bt and Bz, and density and speed increases occurred at 0940 during the data dropout period between 0900 and 1000. Image source: https://www.swpc.noaa.gov/products/real-time-solar-wind

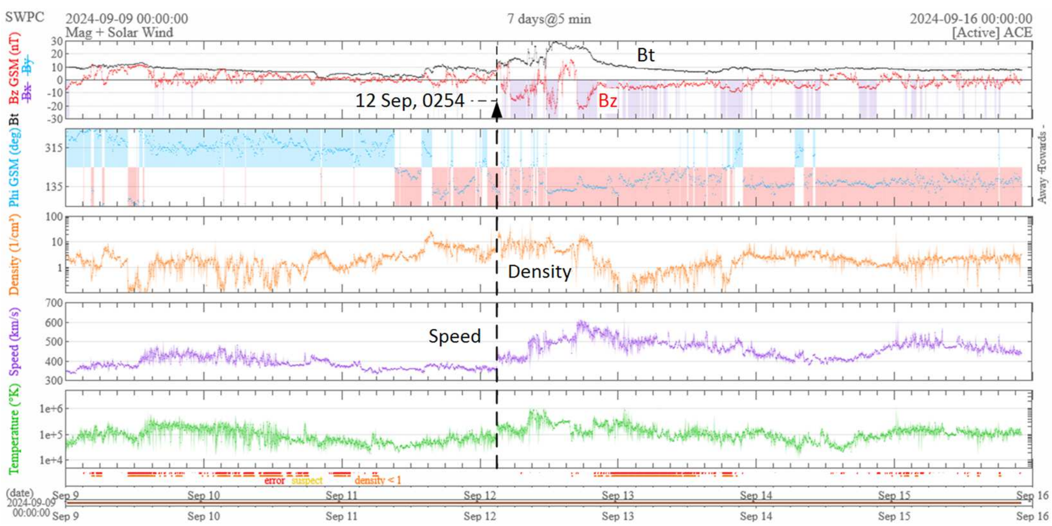

Figure 5 ~ ACE spacecraft data for the 7-day period 9 – 15 September. Bz moved negative starting early on 12 September with periods of sustained negative values days afterwards. The solar wind speed peaked about midday and then slowly decreased. Image source: Same as previous.

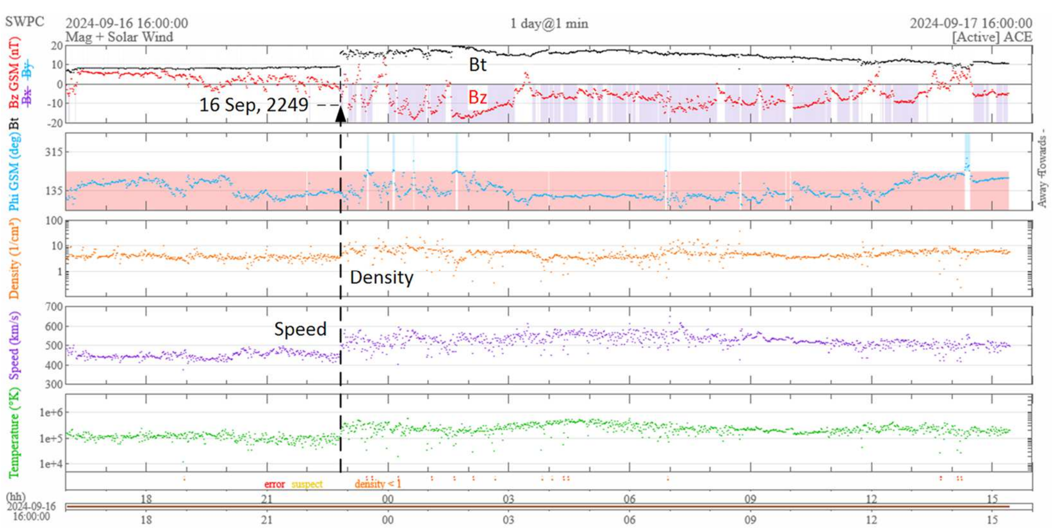

Figure 6 ~ ACE spacecraft data for the 24 hour period starting 1600 on 16 September. Bt increased rapidly at 2249 upon shock arrival. Bz turned negative at the same time and remained mostly negative until 18 September. Image source: Same as previous.

Auroral Electrojets: A result of IMF and geomagnetic field merging is an opening in the magnetosphere that allows energetic charged particles in the solar wind to enter high latitude areas in Earth’s northern and southern hemispheres. These donut-shaped areas are called *Auroral Ovals* and mark the high latitudes regions where open magnetic field lines have their footprint on Earth. Generally horizontal current systems flow in the Auroral Oval between about 100 and 150 km altitude (E-region ionosphere). These currents are called the *Auroral Electrojets* (figure 7).

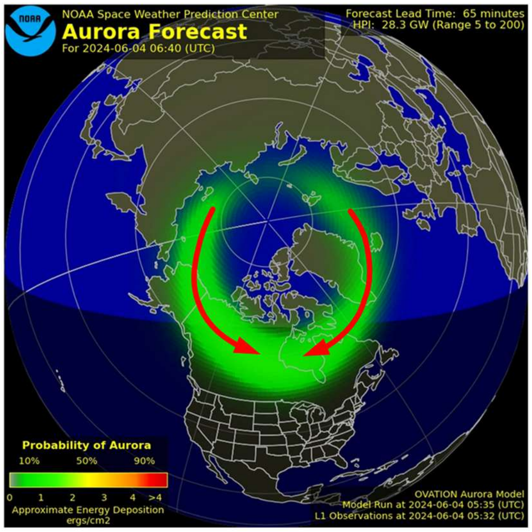

Figure 7 ~ The Auroral Oval is the green donut-shaped area centered on the geomagnetic north pole in this forecast image from NOAA. Magnetic field lines thread the oval and enter Earth's surface directly below. The red arrows indicate the eastward and westward Auroral Electrojets that flow at 100 to 150 km altitude. The Auroral Oval expands during geomagnetic disturbances, carrying the electrojets to lower latitudes. Underlying image source: https://www.swpc.noaa.gov/products/aurora-30-minute-forecast

The particles from the solar wind follow the magnetic field lines down toward Earth where they collide with the atoms and molecules in the atmosphere. The collisions increase the ionization – electron density – in the ionosphere. The increased density and associated conductivity is accompanied by increased Auroral Electrojet currents. The currents are measured by their effects on the local magnetic fields at high latitude observatories around the world and summarized in the AE, AU, AL and AO indices (figure 8, 9, 10 and 11). The magnetic fields measured by the ground magnetometers at both Anchorage and HAARP are influenced by the associated current systems. Magnetic disturbances push the ovals to lower latitudes and the Auroral Electrojets can then flow directly above the two observatories.

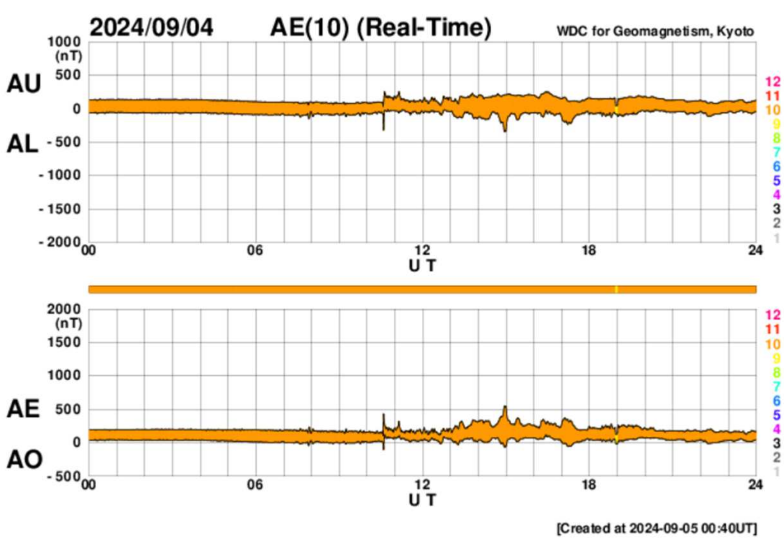

Figure 8 ~ AE indices for 4 September. The Sudden impulse at 1030 UTC was captured in these measurements, and there was a little activity afterwards. However, the AE index only exceeded 500 nT for a very brief period about 4.5 hours after the impulse. The trace envelope color indicate the number of stations reporting (see right scale). Image source: https://wdc.kugi.kyoto-u.ac.jp/ae_realtime/

Because of their low altitude, the Auroral Electrojets can produce large ground disturbances. A typical range of these disturbances is 100 to 1000 nT but much larger disturbances are possible during strong magnetic storms. The Auroral Electrojet index plots during the events in September reached moderately high levels up to about 1500 nT. It is important to remember that these plots are global representations of the AE indices. An individual magnetometer at high latitudes will record the effects of localized Auroral Electrojet currents, which are indicated by the local magnetic field variations.

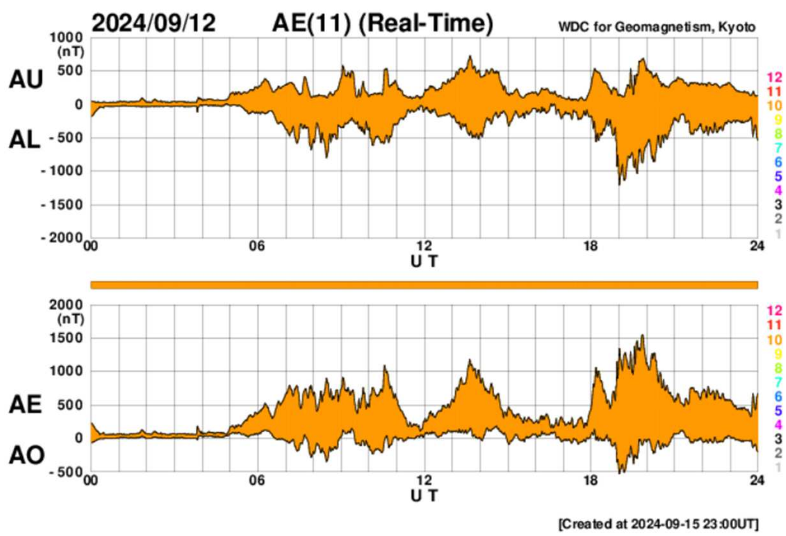

Figure 9 ~ AE indices for 12 September. In contrast to 4 September, the impulse at 0350 UTC on 12 September was followed by far higher electrojet currents throughout the day with the AE index approaching 1000 nT a few hours later and exceeding 1500 nT for a brief period about 16 hours later. Image source: same as previous.

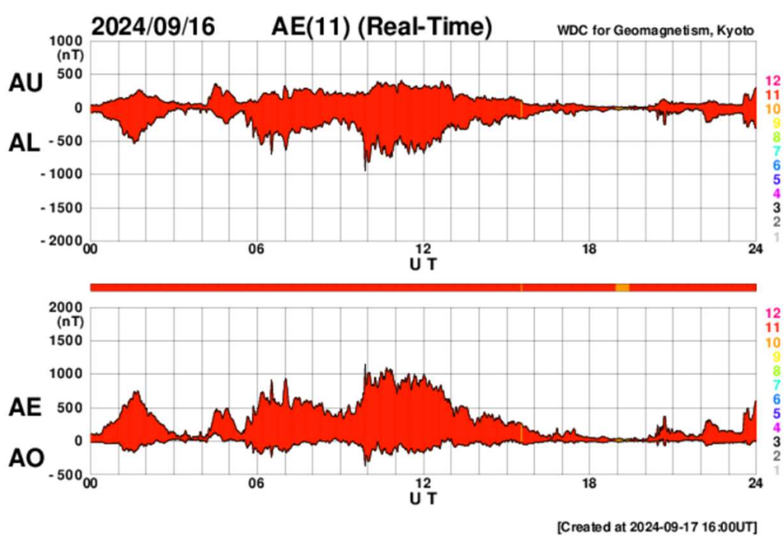

Figure 10 ~ AE indices for 16 September. The impulse late in the day at 2329 UTC was preceded several hours before by relatively high Auroral Electrojet activity due to a coronal hole high-speed stream and its embedded IMF. Since the Sudden Impulse occurred almost at the end of the day, its effects spilled over to the next day as shown in the following figure. Image source: Same as previous.

The AU and AL define the upper and lower envelopes of magnetic measurements from selected northern hemisphere high-latitude stations and express the strongest current intensity of the eastward and westward Auroral Electrojets, respectively, at any given time.

AE is the difference between AU and AL and AO is the average of AU and AL at any given time. Thus, AE represents the overall or peak-to-peak activity of the electrojets and is always positive. AO provides a measure of the equivalent current flows and may be positive or negative at any given time. AO was weak but positive during

4 September, indicating a small eastward current flow in the Auroral Oval. AO was primarily negative during the disturbances on 12 and 16 September, indicating a westward current flow.

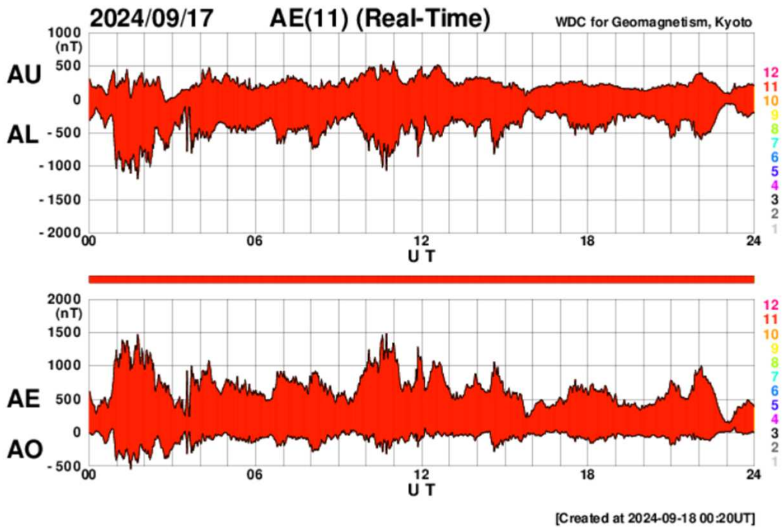

Figure 11 ~ AE indices for 17 September to show the after-effects of the late 16 September Sudden Impulse. The AE index reach 1500 nT within a couple hours of the Sudden Impulse and exceeded 500 nT for almost the entire 24 hour UTC day. Image source: Same as previous.

Magnetograms: The relatively weak eastward electrojet on 4 September produced little magnetic effect at the Anchorage and HAARP observatories (figure 12). The east-west component of the local magnetic fields (By, red trace) at these observatories usually swells each day as the Sun heats up the ionosphere above the stations from about 1200 to 1800 UTC each day. In this case, the pattern was little affected by the electrojets. However, as seen in the north-south component (Bx, blue trace), the Sudden Impulse immediately raised the magnetic flux density, which then slowly tapered off for several hours afterwards.

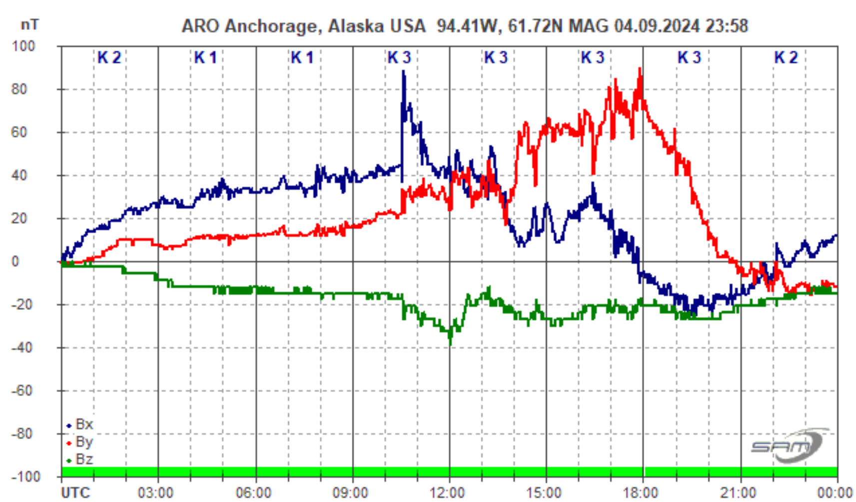

Figure 12.a ~ Magnetic field measurements at Anchorage Radio Observatory for 4 September. Note the vertical scale is 20 nT div^{-1}. The sudden impulse primarily affected the north-south component (blue trace, Bx) with a step-change at 1030 UTC followed by a slow decrease. Smaller step-changes are visible in the east-west component (red trace, By) and vertical component (green trace, Bz). The sudden impulse amplitude at Anchorage (vector sum of Bx and By) was approximately 56 nT. Image credit: © 2024 W. Reeve

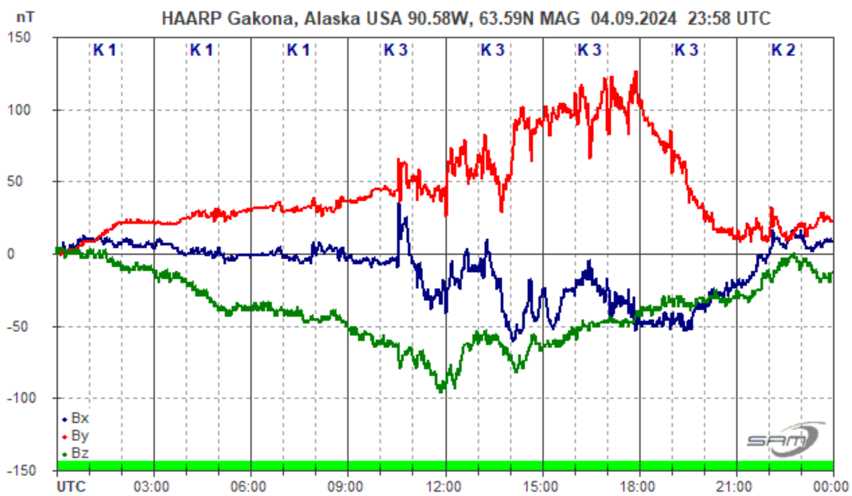

Figure 12.b ~ Magnetic field measurements at HAARP Radio Observatory for 4 September. Note the vertical scale in this plot is different than Anchorage at 50 nT div^{-1}. The sudden impulse effects are similar to Anchorage except that the east-west (By) component has higher amplitude, but the overall amplitude is 58 nT, only slightly higher than Anchorage. Image credit: © 2024 W. Reeve

The Auroral Electrojets on 12 September were much stronger, producing both bays and peaks in the local magnetic field components and indicating the complexity of the effects (figure 13). The event on 16 September produced a relatively large bay the next day (figure 14). A bay, or decrease, indicates that the magnetic field produced by the Auroral Electrojets opposed the local magnetic field while a peak indicates an enhancement. The SAM-III magnetograms at both Anchorage Radio Observatory and HAARP Radio Observatory displayed elevated K-indices throughout most of the day after the impulses on 12 and 16 September, although the K-index did not reach the highest possible value of K9 at either location.

Figure 13.a ~ Anchorage magnetogram for 12 September. The vertical autoscale function of the SAM_VIEW software stepped to 1000 nT due to the high magnetic flux density at about 0930 following the Sudden Impulse. The impulse was almost invisible at this scale so the time from about 0300 to 0415 has been expanded in the inset to show more detail. The sudden impulse amplitude at Anchorage (vector sum of Bx and By) was approximately 76 nT.

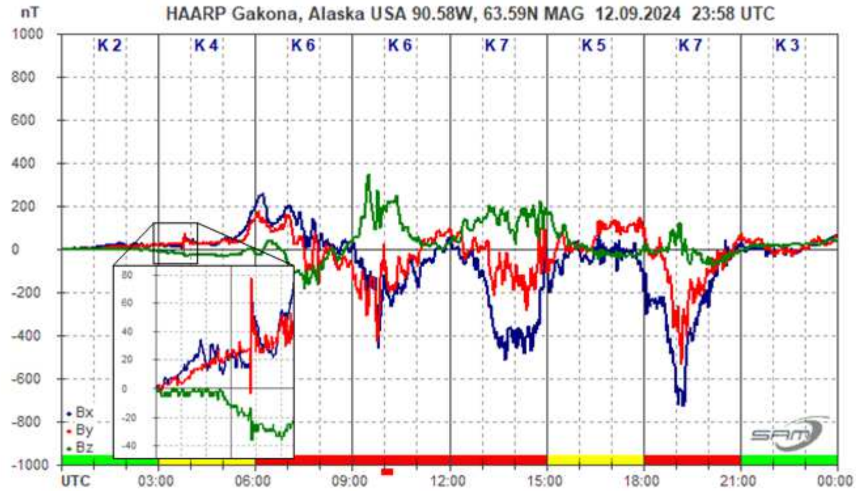

Figure 13.b ~ HAARP magnetogram for 12 September. As at Anchorage, the Sudden Impulse was almost invisible so the time range from about 0300 to 0415 has been zoomed-in. All three components show evidence of the impulse, including about 10 nT in the vertical component Bz. The sudden impulse amplitude at HAARP (vector sum of Bx and By) was approximately 90 nT. Note the very similar but imperfect match between the impulse and full day field variations at Anchorage and HAARP. Part of the difference is due to different magnetic environments, including magnetic latitude, but some differences could arise because of the different models of fluxgate sensors at each site (FG3+ at HAARP and FGM-3 at Anchorage).

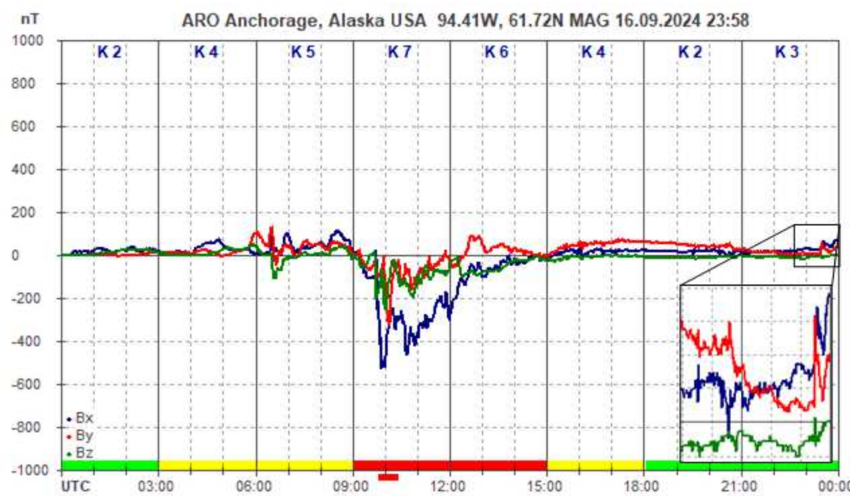

Figure 14.a ~ Anchorage magnetogram for 16 September annotated with the last three hours of the UTC day zoomed-in. All three components show evidence of the impulse (near right edge), including about 15 nT in the vertical component Bz. The sudden impulse amplitude at Anchorage was approximately 63 nT. Note the bay seen in the inset in the east-west component (By, red trace) during the 3-hour period leading up to the Sudden Impulse.

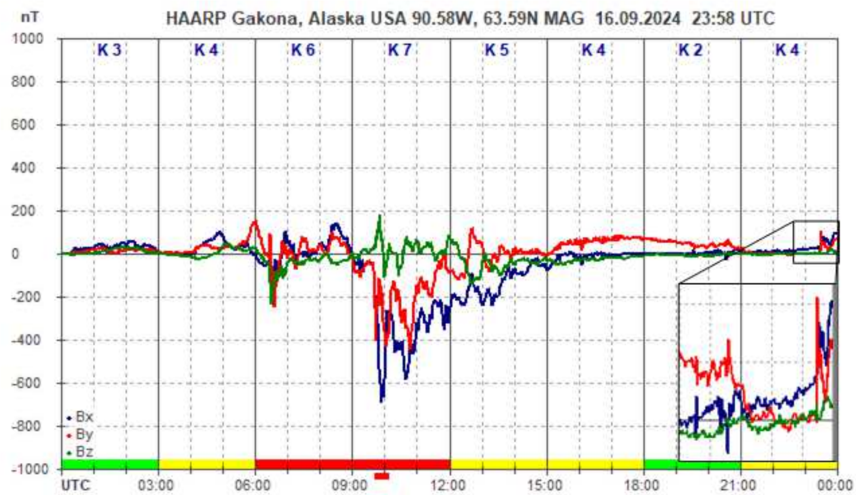

Figure 14.b ~ HAARP magnetogram for 16 September annotated with the last three hours of the UTC day zoomed-in. The scale in the inset is 50 nT Div^{-1}. The sudden impulse amplitude at HAARP was approximately 120 nT. Note the periodicity in variations of both Bx and By during the 0900-1200 and 1200-1500 synoptic periods prior to the Sudden Impulse. Similar periodicities appear in the Anchorage magnetogram but are lower amplitudes. The periods are too long to be classified as Ultralow Frequency (ULF) Waves and could be caused by *Periodic Density Structures* in the solar wind or substorm energy loading and unloading in the magnetosphere (step 7 in the Dungey Cycle described in the Interplanetary Magnetic Field section).

Discussion: Although storms (≥ K5) occurred at both observatories after the impulses on 12 and 16 September, the magnetic deflections only reached about 600 and 700 nT in Bx and By for a short time. Nevertheless, these peak deflections were significant fractions (~5% of Bx and ~10% By) of the ambient magnetic field components (table 2).

Table 2 ~ Ambient magnetic flux densities for September 2024 at the Anchorage and HAARP stations based on World Magnetic Model (2019-2024). Data source: https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml#igrfwmm

Observatory	**Bx, north-south (nT)**	**By, east-west (nT)**	**Bz, vertical (nT)**
Anchorage	14 665	3 821	52 857
HAARP	13 416	3 910	53 838

The active regions on the Sun responsible for the CMEs discussed in the present article eventually rotated out of view and the space weather substantially calmed down on 18 September. However, during the last 12 days of September there were several brief storm intervals that involved CME trailing influences or near-misses and coronal hole high-speed streams.

The AE index variations shown previously are moderate compared to the very strong storm on 10 to 13 May 2024 (often called the *May Superstorm*) during which the AE index went off-scale (> 2000 nT). Not surprisingly, both Anchorage and HAARP magnetometers displayed a K-index of K9 (the highest on the K-index scale) on those same days. The May storm was unique because of its high and sustained intensity and will be the subject of a future article.

Readers may refer to several previous articles about Sudden Impulses recorded by the SAM-III magnetometers in Alaska:
https://reeve.com/RadioScience/Radio%20Astronomy%20Publications/Articles_Papers.htm#Observations

Instrumentation: The block diagrams for the SAM-III Magnetometers at Anchorage and HAARP show that the two installations are nearly identical (figure 15). The differences are listed in table 3. Both stations use the SAM_VIEW software to display and log the three magnetic components. Real-time magnetograms are available at: https://reeve.com/SAM/SAM_simple.html (Anchorage) and https://reeve.com/SAM/SAM-HAARP/SAM-HAARP_simple.html (HAARP).

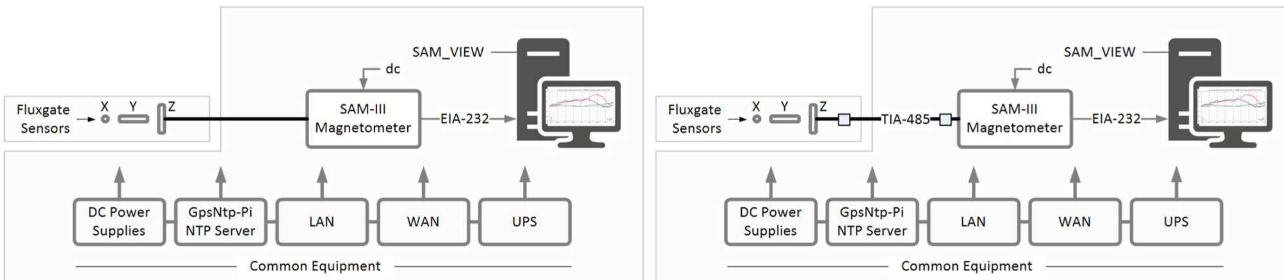

Figure 15 ~ SAM-III Magnetometer block diagrams for Anchorage (left) and HAARP (right). The two are operationally identical and differ only in a few technical details (see text).

Table 3 ~ Differences between magnetometer stations.

Observatory	**Anchorage**	**HAARP**	**Remarks**
Sensor type	FGM-3	FG-3+	Performance nearly identical
Sensor voltage	12 Vdc	5 Vdc	Anchorage has 5 V voltage regulators at the sensors whereas HAARP has them on the controller
Sensor transmission	Cable only	TIA-485 + Cable	HAARP uses CAT5E cable and TIA-485 transmission interfaces

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[Seki] Seki, K., et al, A Review of General Physical and Chemical Processes Related to Plasma Sources and Losses for Solar System Magnetospheres, Space Science Reviews, August 2015, DOI 10.1007/s11214-015-0170-y

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