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Key Points:
- The 23-27 May 1967 event was a "Great" solar and geospace storm
- First Air Force Solar Forecasting Unit partially mitigated the impacts of extreme solar radio bursts on U.S. military
- The storm led to military recognition of space environment effects as an operational concern and helped establish a forecasting system

Supporting Information:
- Supporting Information S1
- Table S1

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The May 1967 great storm and radio disruption event: Extreme space weather and extraordinary responses

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Abstract Although listed as one of the most significant events of the last 80 years, the space weather storm of late May 1967 has been of mostly fading academic interest. The storm made its initial mark with a colossal solar radio burst causing radio interference at frequencies between 0.01 and 9.0 GHz and near-simultaneous disruptions of dayside radio communication by intense fluxes of ionizing solar X-rays. Aspects of military control and communication were immediately challenged. Within hours a solar energetic particle event disrupted high-frequency communication in the polar cap. Subsequently, record-setting geomagnetic and ionospheric storms compounded the disruptions. We explain how the May 1967 storm was nearly one with ultimate societal impact, were it not for the nascent efforts of the United States Air Force in expanding its terrestrial weather monitoring-analysis-warning-prediction efforts into the realm of space weather forecasting. An important and long-lasting outcome of this storm was more formal Department of Defense-support for current-day space weather forecasting. This story develops during the rapid rise of solar cycle 20 and the intense Cold War in the latter half of the twentieth century. We detail the events of late May 1967 in the intersecting categories of solar-terrestrial interactions and the political-military backdrop of the Cold War. This was one of the "Great Storms" of the twentieth century, despite the apparent lack of large geomagnetically induced currents. Radio disruptions like those discussed here warrant the attention of today's radio-reliant, cellular-phone and satellite-navigation enabled world.

1. Introduction

1.1. Intersection of Nature and Politics

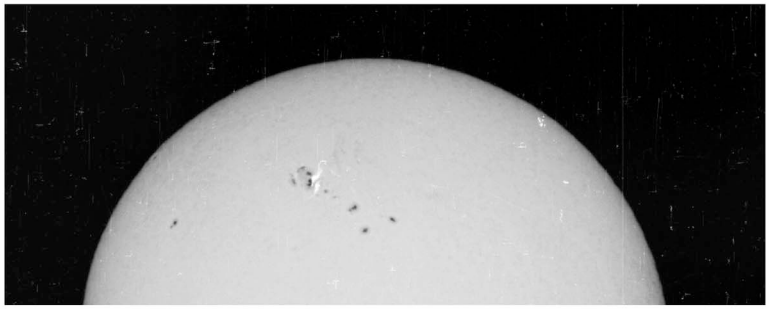
In late May 1967 during the rapid rise of solar cycle 20, one of the most active regions of the decade, McMath Region 8818, rotated onto the Earth-facing solar disk during Carrington Rotation 1521. Figures 1a–1c provide Environmental Science Services Administration (ESSA) details of the event, along with hydrogen alpha (H α) images of the 23 May 1967 flares from Sacramento Peak Observatory operated by the United States Air Force (USAF). Solar radio bursts (SRBs) and plasma eruptions from the region filled the interplanetary regime. Radio technologies of the day were severely tested. The quote (below) from a presentation by *Citrone* [1995] addresses the roles of two USAF agencies—Air Weather Service (AWS) and North American Air Defense (NORAD) Command in responding to the event—and provides insight into the gravity of the situation faced by Department of Defense (DOD) during these disturbances:

> "Probably the first significant operational impact came from a major solar flare and the resultant geomagnetic storm in May, 1967. AWS notified NORAD in real time of the event and the associated mission impacts. However, outside agencies were not aware of the space environmental factors and made uninformed decisions without considering the drastic impacts the event imparted to NORAD's early warning systems, which have a direct bearing on decisions being made at the highest levels of the US government. As a result of this near incident, the need to incorporate real-time space weather information into the Air Force decision-making process was made obvious to many, and several major efforts were undertaken to greatly improve the operational capability of the AWS Space Environmental Support System."

a

232	N24	5/18	East limb passage of one of the greatest activity complexes of Solar Cycle 20. Composed of three overlapped spot groups at time of first appearance, two of which were growing.
		5/20	Birth of fourth spot group on southern border of complex. Westward relative motion of this group, with respect to large spots to the north, may have contributed to conditions for great flare of 21 May in center of complex.
		5/21	"Collision" between central and western members of the complex, as growth and expansion of central member moved its leader spot into the follower plage of the western member. Large flare occurred over the neutral line between the groups.
		5/23	"Collision" and merger of leader of easternmost member with follower of central member, creating large "delta" magnetic configuration. Closest separation between the opposite-polarity spots coincided with great white-light, proton flare at 1840 UT (see *UAG Report 5*). These spots moved in a rotary pattern with respect to one another during 21-26 May.
		5/28	Additional great flare over the "delta" configuration.

b



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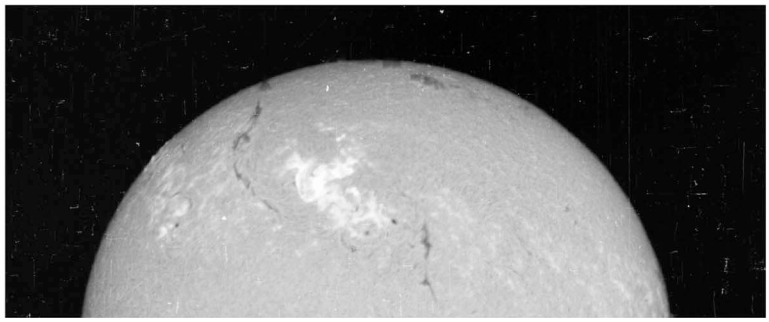

Figure 1. (a) Notes on the dynamics of McMath Region 8818, extracted from *McIntosh* [1979, p. 84]; (b) May 23 1967, 1840:50 UT, H α wing image, 656.28 nm, $\Delta\lambda = \pm 0.2$ nm; (c) 1844:00 UT, H α emission 656.28 nm, line center. North is at the top. West is to the right (Courtesy of National Solar Observatory).

This quote, which originates in unclassified AWS documents from the early 1980s [*Department of the Air Force*, 1980; *Townsend et al*., 1982], delicately sidesteps the circumstances of the situation that clearly involved an uneven response to a solar-geophysical storm.

Compared to the relative quiet of the first part of the month, major solar storms and attendant radio emissions developed on 21 May and continued through 28 May 1967. One of the largest geomagnetic storms on record began on 25 May. These geophysical conditions were intertwined with other factors that required vigilance on the part of the U.S. military. Cold War tensions were playing out in May 1967 with high-stakes developments in the Vietnamese demilitarized zone and the escalation to the June 1967 war in the Middle East [e.g., *United States Department of State*, 2009a, 2009b; History.com, http://nssdc.gsfc.nasa.gov/nmc/experimentDisplay.do?id=1964-040A-03, accessed on 8 May 2016]. We shed light on how the largest recorded solar radio burst of the twentieth century, on 23 May 1967, was a near tripwire in the tense political and military landscape of the time.

1.2. Cold War and Military Background

We provide a brief overview of the roles of USAF commands and agencies involved in the May 1967 near incident. The intense May 1967 solar activity, which we describe in section 2, took place against a backdrop of the ongoing Cold War marked by the extraordinary buildup of nuclear weapons as part of the doctrine of mutually assured destruction. Tensions between the eastern and western blocs of nations played out in direct interactions between super powers and as activities in distant lands where surrogate politics could easily produce flashovers.

The USAF had a primary role in maintaining the delicate balance of nuclear threat for the Western bloc [*Winkler and Webster*, 1997]. Two key players were the USAF Strategic Air Command (SAC) and the North American Air Defense Command (NORAD), which later replaced "Air" with "Aerospace." After World War II SAC was established with a mission of conducting worldwide long-range offensive operations, first conventional and then nuclear [*Strategic Air Command*, 1991]. From the early 1960s to 1990 SAC maintained an aerial command post and a constant in-air presence. During the peak of the Cold War one third of the entire bomber force was on alert at any given time [*DeBerry et al*., 1997].

SAC developed an Alert Force Concept and exercised it often [*Narducci*, 1988]. For the aerial fleet these were multiminute scrambles to prepare bomber aircraft for launch in the shortest possible time [e.g., *Kelley*, 2016, Introduction]. As noted on one website dedicated to SAC history (http://www.lincolnafb.org/), "To keep airmen trained and ready for alerts, SAC headquarters often dispatched alert exercise messages to its bases. These exercises ranged from Alpha, Bravo, Coco and Delta. Alpha exercises included the crews scrambling to their plane, while Bravo included the start up of the aircraft. Coco exercises involved the aircraft taxiing to the runway and readying for takeoff before the exercise would be called off. These alerts were quite rare, but Delta exercises were the rarest as they sent the aircraft into the air." Radio communications for command and control of the Alert Forces were crucial if aircraft took to the air. SAC's primary communication system, GIANT TALK relied on the high-frequency (HF) 6–30 MHz band, with supplemental communications at higher frequencies.

Air defense was entrusted to a different entity. In late 1957, Canada and the U.S. agreed to create the binational North American Air Defense Command to centralize operational control of North American continental air defenses against the threat of Soviet bombers. NORAD was headquartered in Colorado Springs, CO, USA. During the early 1960s NORAD began operating the Ballistic Missile Early Warning System (BMEWS), designed to track space objects and detect incoming intercontinental ballistic missiles (ICBMs) [*Schaffel*, 1990]. Three high-latitude BMEWS radar sites, operating at 440 MHz, monitored the polar skies and provided ~15 min warnings to the U.S., Canada, and the United Kingdom [*Stone and Banner*, 2000]. On 15 May 1967 NORAD accepted as "fully operational" a major upgrade to the BMEWS system [*Del Pappa and Warner*, 1987]. NORAD and SAC operations were inextricably linked as they shared early warning data; however, decisions related to the data could result in independent actions.

In 1948 Dr. Donald Menzel, a Harvard University astronomer, laid the groundwork for AF solar observatories in an attempt to continue radio propagation studies for the military in the post World War II era [*Liebowitz*, 2002]. After the launch of Sputnik-1 the USAF Air Weather Service (AWS), which provided meteorological support for USAF and Army operations, extended its efforts into solar and geophysical forecasting by sending a few weather officers (three in the first round) to obtain advanced degrees in related areas. These officers provided the technical leadership for the AWS Solar Observing and Forecasting Network (SOFNET), a network tasked to support NORAD and its radars, some of which experienced solar and auroral interference. Under the guidance of USAF Major Roger Olson solar prediction "tests" began in late 1962 at Headquarters (HQ) AWS, followed with regular predictions from a facility at Ent AFB in Colorado Springs, CO, USA in the latter half of 1964 [*Markus et al*., 1987]. By September 1965 several solar observatories were providing data to the AWS Fourth Weather Wing (4WW) via SOFNET. In May 1967 four solar observatories in the U.S., as well as observatories in Greece and the Philippines, were hosting AWS and Air Force Cambridge Research Laboratory (AFCRL) solar observers, some of whom augmented local civilian observing staff.

To ingest SOFNET data and disseminate related information, the 4WW Solar Forecast Center began operations with one forecaster and one observer in the autumn of 1965 at Ent AFB. Shortly thereafter, the Center, also known as Detachment 7, Operating Location 10 (DET 7 OL-10), expanded and moved to the NORAD Cheyenne Mountain Complex (NCMC) in Colorado to be colocated with decision makers.

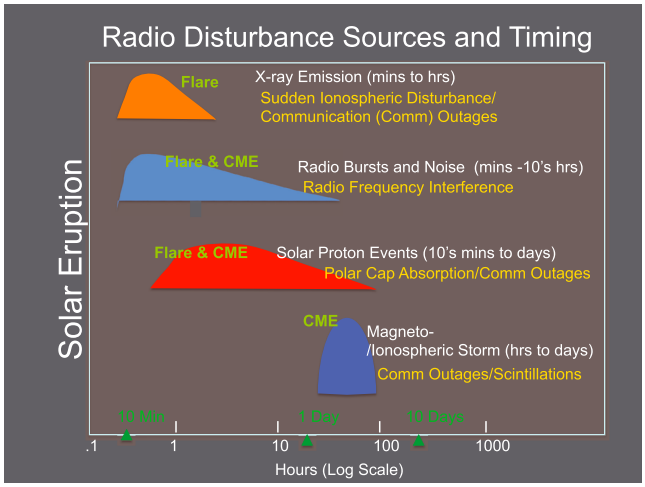

Figure 2. Simplified summary of radio disturbances generated by a single solar eruption. Each colored element represents a different disturbance category. The light green labels show the origin at the Sun. The white labels show the space weather disturbance categories commonly discussed in the literature. The yellow labels name the effects observed at Earth. The top three categories have rapid onsets and slower decays. The horizontal axis is in log hours in time since emission at the Sun. The dark green labels provide reference times in minutes and days. As an example, energetic protons may be generated by flare processes and begin arriving at Earth in as little as 20 min. They may continue be energized by coronal mass ejections (CMEs) and be present at Earth for some time after CME passage. Log scaling tends to compress larger values; hence, the visual duration of CMEs appears short in this diagram. In fact, CME's and SPEs both influence geospace for hours to days. More complex storms like those discussed in this manuscript will have multiple overlying events. This image is patterned after one used by the Air Force Research Laboratory

This also marked the beginning of 24 h a day DOD space weather operations. On 1 April 1966 the 4WW issued its first forecasting manual: Fourth Weather Wing Manual 105-1, Forecasting Solar Activity and Geophysical Response [*4th Weather Wing 4WWM 105-1*, 1966], authored by Colonel Charles (C.K.) Anderson, Commander of DET 7, 4WW, and his Scientific Services Officer, Captain Allan Ramsay. By May 1967 Detachment 7 established a forecast routine with a primary forecast at 21 UT and three supplementary forecasts at 03, 09, and 15 UT. An extended forecast was issued weekly. Routine briefings were provided to NORAD. Thus, by the time of the May 1967 storms there was an established methodology for communicating space environment concerns to NORAD. Simultaneously, AF (and SAC) interest in ionospheric forecasting was on the rise. Test ionospheric forecasts began in late 1966, with full time ionospheric forecasting underway at NCMC in late 1968. The interval between the ionospheric test forecasts and a fully functioning ionospheric forecasting effort is of significant interest because it bracketed the great solar and geomagnetic storms of late May 1967.

Civilian interest in solar and geophysical activity was also increasing as the nation geared up for human spaceflight missions and an eventual trip to the Moon. To better characterize and predict hazardous space environmental conditions in support of NASA, ESSA's Space Disturbances Laboratory (SDL) was created from the former Central Radio Propagation Laboratory in 1965 [*Olson*, 1969]. The latter organization leveraged observations from the University of Colorado's High Altitude Observatory to provide "radio weather" forecasts for a broad community of users in the WWII and post-WWII era. SDL operated the Space Disturbances Forecast Center (SFDC), which is now the National Oceanic and Atmospheric Administration (NOAA) U.S. Space Weather Prediction Center (SWPC). ESSA also exercised administrative oversight of the Aeronomy and Space Data Center (now the Solar-Terrestrial Physics (STP) unit of the U.S. National Centers for Environmental Information (NCEI)). Much of the supporting information for this manuscript is derived from ESSA's Upper Atmosphere Geophysics Report-5 (UAG-5) [*Lincoln*, 1969] and Solar-Geophysical Data, IER-FB-274 and IER-FB-275, ESSA [*Solar-Geophysical Data*, 1967a, 1967b].

1.3. A Brief Guide to Solar and Geomagnetic Disturbances With Emphasis on Radio Effects

To assist those readers unfamiliar with the myriad of space weather radio effects, we provide a short guide to sources and timing of radio disturbances and a schematic of these in Figure 2. The most geoeffective space weather storms often arise from multiple solar emissions in or above sunspots threaded by strong, twisted magnetic field. These regions, formerly called plage regions, are now called Active Regions (AR). When energy density in AR magnetic fields reaches a tipping point, the fields reconfigure, producing bursts of electromagnetic energy (flares) across a broad spectrum of wavelengths: X-ray, extreme ultraviolet (EUV), UV, visible, and radio emissions. Some very strong flares produce gamma ray and intense white-light emissions. All electromagnetic emissions, which travel at light speed, reach Earth in roughly 8 min. Solar radio bursts (SRBs) can

cause immediate radio frequency interference (RFI) in systems that receive and/or process radio signals, Radars and Global Navigation Satellite Systems (GNSS), of which the U.S. Global Positioning System (GPS) is an example, are two types of impacted systems. (See Figure 8 of *Nita et al.* [2002] for a schematic of a typical solar radio burst spectrum.) Additionally, flare X-ray and EUV emissions interact with Earth's upper atmosphere and change ionization levels, altering the upper atmosphere's ability to propagate radio signals, and often producing high-frequency (HF) signal absorption [see *Thomson et al.*, 2005]. These effects fall under the general category of sudden ionospheric disturbances (SIDs). RFIs and SIDs are considered prompt flare effects.

Often, an additional consequence of solar magnetic field reconfiguration is the eruption of a coronal mass ejection (CME)—a magnetized cloud of plasma rising out of or near the flare site. Although CMEs and flares can develop independently of each other, the largest solar flares are almost always accompanied by fast CMEs that propagate outward at supersonic speeds. As CMEs traverse the outer solar atmosphere, they disturb the plasma in the solar atmosphere creating a new set of radio signals (noise) that extend the noise from the original burst disturbance. CMEs, though traveling at supersonic speeds in the solar atmosphere and in the interplanetary medium, are the "slow movers" in the chain of disturbances that arrive at Earth's orbit. The fastest CMEs arrive at Earth in about a day; however, 2–4 days is more typical. When these magnetized plasma clouds pass Earth, sometimes causing sudden storm commencements (SSCs), their interactions with Earth's magnetic field can cause geomagnetic disturbances and intensify ionospheric storms. In turn, these storms can disrupt radio communication on a regional basis. CME arrival may also generate magnetospheric compression events, promote geomagnetically induced currents (GICs) at the ground, and enhance currents and fluxes of energized particles that threaten satellites with solar wind particles and particles from the radiation belt. Radio noise from CMEs can be present for tens of hours. Geomagnetic effects of CMEs are generally long-delay effects.

Flares and CMEs can generate another form of space weather disturbance called solar energetic particle events. These are composed of highly accelerated electrons and protons energized at the flare site or at the leading edge of fast CMEs. Because protons are the primary momentum carriers, the associated disturbances are usually called solar proton events (SPEs) events. High-energy SPEs can reach Earth in 20 min to a few hours after the particles are accelerated. The broad shocks ahead of fast CME's continually energize such particles creating long-lasting (gradual) SPEs that are called radiation storms. Radiation storms can damage satellites, harm astronauts, and cause long-lived HF radio communication disruptions due to signal absorption in the polar regions called polar cap absorption (PCA) events. These are short-delay effects.

Each of these events creates in their own way different radio disturbances, first by noise from the SRBs, and by effects of X-ray and EUV in the lower and upper ionosphere, respectively (mostly on a global scale on the dayside), then by deep ionospheric ionization from the energetic protons at high latitudes in both hemispheres, causing HF radio absorption. Lastly, with Earth arrival of the CME, magnetospheric and ionospheric storms cause other types of radio disturbances, primarily from dusk to dawn in the near-equatorial latitudes and on Earth's nightside near the auroral zones. Electric fields can promptly penetrate to low latitudes causing otherwise marginally stable layers of the ionosphere to overturn creating equatorial plasma bubbles that scintillate radio signals. On slightly longer timescales energy from the magnetosphere cascades to Earth's upper atmosphere where it can cause compositional changes, ionospheric patches and perturbations, enhanced satellite drag, and aurora. There is growing evidence that the largest high-latitude auroral disturbances can produce waves in Earth's atmosphere that propagate to low latitudes, giving rise to additional disturbances in the form of radio signal scintillation near the magnetic equator. Scintillations mainly affect current-day GNSS and satellite communication.

Briefly, solar eruptions give rise to a chain of events whose effects window can extend from just over 8 min to several days (or longer if Earth's inner radiation belts are disturbed). Radio technologies are unique in that they can suffer disruptions from every aspect of a solar space weather disturbance, and even from atmospheric effects that are quite secondary. In many cases radio disruption is from only one storm source, but during extreme events all sources may contribute. The effects tend to be frequency and system dependent, making them very challenging to diagnose and predict. For additional discussion of and references for these topics see *Lang* [2009] and *Baker and Lanzerotti* [2016].

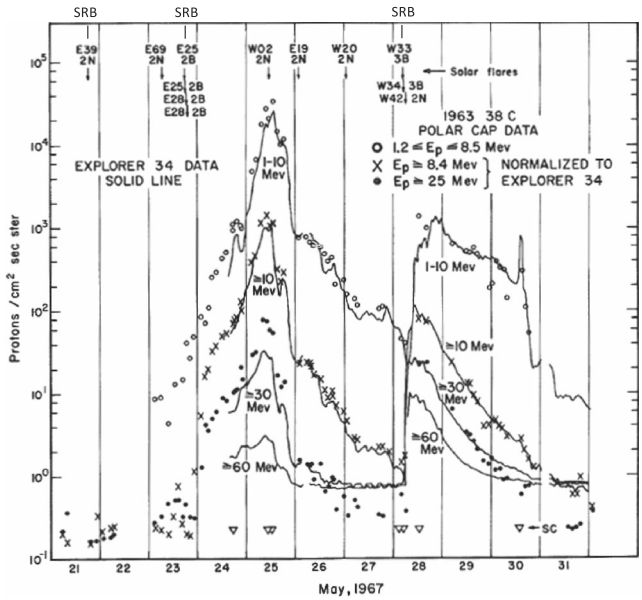

Figure 3. Flare timing and solar energetic particle data for 21–31 May 1967 from Satellites 1963-38C and Explorer 34 from *Bostrom et al.* [1969] ESSA UAG-5 report. Solar flare locations in east and west longitude with respect to central are on the top line. Numbers followed by letters N or B give relative size and qualitative emission level (N = normal, B = brilliant). The solar radio burst information is extracted from *Castelli and Barron* [1977]. Explorer 34 (date in solid curves) was launched while the storm was in progress on 24 May 1967.

2. May 1967 Solar-Geophysical Background and Details—What We Know Now

Here we present the solar-geophysical "backstory" for May 1967 derived from publications spanning four decades and from the recollections of those involved in the actual event and postevent analyses. Figure 3 gives a temporal reference for the SRBs, flares, SPEs, and sudden commencement (SC) events. We provide details of the solar bursts because they were at the heart of the situation. We also provide a general discussion of the geospace response and tabulate the details in a table for quick reference.

2.1. The Solar Backstory: Rising Solar Activity in McMath Region 8818, 21–31 May 1967

McMath Plage Region 8818 (Figure 4) appeared at the east solar limb on 17 May, passed disk center on 25 May, and rotated off the western limb on 31 May. It produced 76 flares of importance ≥ 1 (coverage ≥ 100 millionths of solar disk area) during its Earth-facing passage [*Lindgren*, 1968]. The 18 May 1967 ESSA H α Synoptic Chart notes (Figure 1) report an "East limb passage of the one of the greatest activity complexes of Solar Cycle 20." The plage region first showed itself to be hyperactive late on 21 May. On 21, 23, and 28 May the region produced great radio bursts [*Castelli and Barron*, 1977]. The 21 May event included a white-light flare at solar coordinates N24°, E39°, along with soft and hard X-ray emissions, in addition to Types II, III, IV, and V dynamic radio spectra and 2.8 GHz and 600 MHz radio emissions (see data listings and plots in *Arnoldy et al.* [1969], *Kane and Winckler* [1969a], and *Dodson et al.* [1975]). Subsequently, Pioneer 7, located at 1.06 AU with an Earth-Sun-spacecraft angle of −36.5° (and thus magnetically well connected to the plage region at E39°), recorded an increase in energetic proton flux with energies above 73 MeV [*Simpson and Fan*, 1973].

During the next 2 days complexity and magnetic gradients in the region increased. The ESSA Chart notes for 23 May indicate "Closest separation between the opposite-polarity spots coincided with great white-light, proton flare at 1840 UTC…." At that time when the region extended from 27 to 30°N solar latitude and 25 to 28°E longitude, it produced extraordinary, hours long SRBs, a two-ribbon H α flare, 7 min of localized white-light flare emissions, and multiple hours of enhanced X-ray emissions [*Lincoln*, 1969]. Several measures of dayside SID radio disturbances went off scale. Two midlatitude solar observatories, Sacramento Peak (optical), NM, and Sagamore Hill (radio), MA, observed the events in real time. The peak emissions occurred at approximately sunset in European time zones and near noon local time in the U.S. central states [see *Richmond and Venkateswaran*, 1971, Figure 9]. The northern polar regions, where the BMEWS was based [see *Winkler and Webster*, 1997, figure on p. 38], were nearing 24 hours of sunlit conditions with uninterrupted low elevation solar viewing at many locations.

Following the flare emissions there appeared a long-lived SPE beginning late on 23 May, and a geomagnetic storm with 6 h at $Kp = 9$ and a *Dst* index of −387 nT (the eighth largest *Dst* storm on record), on 25–26 May 1967 [*Cliver and Svalgaard*, 2004]. The cosmic ray Forbush [*Forbush*, 1938] decrease associated with the behemoth plasma cloud(s) lasted into early June of 1967 [see *Carmichael and Steljes*, 1969, Figure 1]. The overall activity was so intense that it merited a special ESSA report [*Lincoln*, 1969]. Evaluation of the

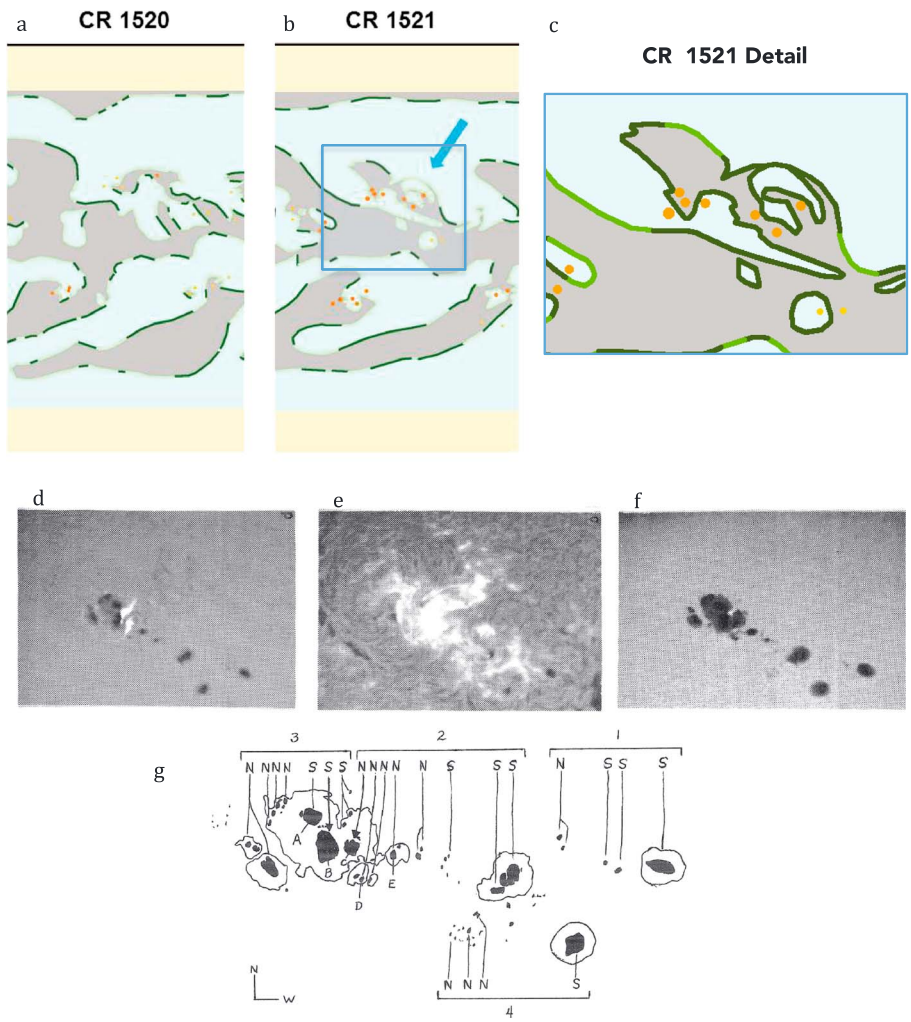

Figure 4. (a–c) Redrawings of portions of hydrogen alpha (H α) synoptic charts of Carrington Rotation 1521 from *McIntosh* [1979, pp. 83, 85, and 87]. Orange dots represent sunspots. Gray areas are regions of closed magnetic field. The yellow zones (above 70°) lack data. (b) The blue box highlights McMath Region 8818, during CR 1521. (c) Enlargement of image in Figure 4b. Sacramento Peak enlarged flare imagery after *DeMastus and Stover* [1967]: (d) H α wing 656.28 nm, $\Delta\lambda = \pm 0.2$ nm; (e) 1844:00 UT, H α emission 656.28 nm, line center; (f) white light, two small dots indicate white-light flare at 1840 UT; (g) magnetic polarities (N = north and S = south) of McMath Region 8818 on 21–25 May measured at the Crimean Astrophysical Observatory from *McIntosh* [1969]. More details on the complex sunspot groups and tight solar magnetic field gradient are available in *McIntosh* [1969], *Malville and Tandberg-Hanssen* [1969], and *MacIntosh and Donnelly*, [1972].

published data indicates there was a long-lasting radio communication and monitoring disruption affecting civilian and DOD customers in the sunlit areas and in the polar caps. In the militarily tense era of 1967 a multi-frequency radio disruption was ripe for misinterpretation.

2.2. Solar Bursts and Emissions Across the Spectrum

On 23 May Howard DeMastus and Rod Stover were on flare patrol at the Sacramento Peak Optical Observatory in support of SOFNET. AF Chief Warrant Officer Walter Clark operated and calibrated five sets of microwave equipment at Sagamore Hill Observatory during the height of the storm on 23 May. Patrick McIntosh from ESSA was monitoring solar activity in Boulder, CO. *DeMastus and Stover* [1967] reported three pulses of flaring between 1805 UT and 2300 UT, including a flare wave that traveled 0.3 solar radii in only 5 min during the second pulse. It was during this pulse that the white-light flare appeared. *Najita and Orrall* [1970] estimate that for a few minutes the solar flare white-light emissions increased by 6% above local quiet background. The incredible 23 May flares were captured on photographic film (Figures 1 and 4) allowing a detailed post-event analysis [see *DeMastus and Stover*, 1969, pp. 5–6]. *Dodson and Hedeman*

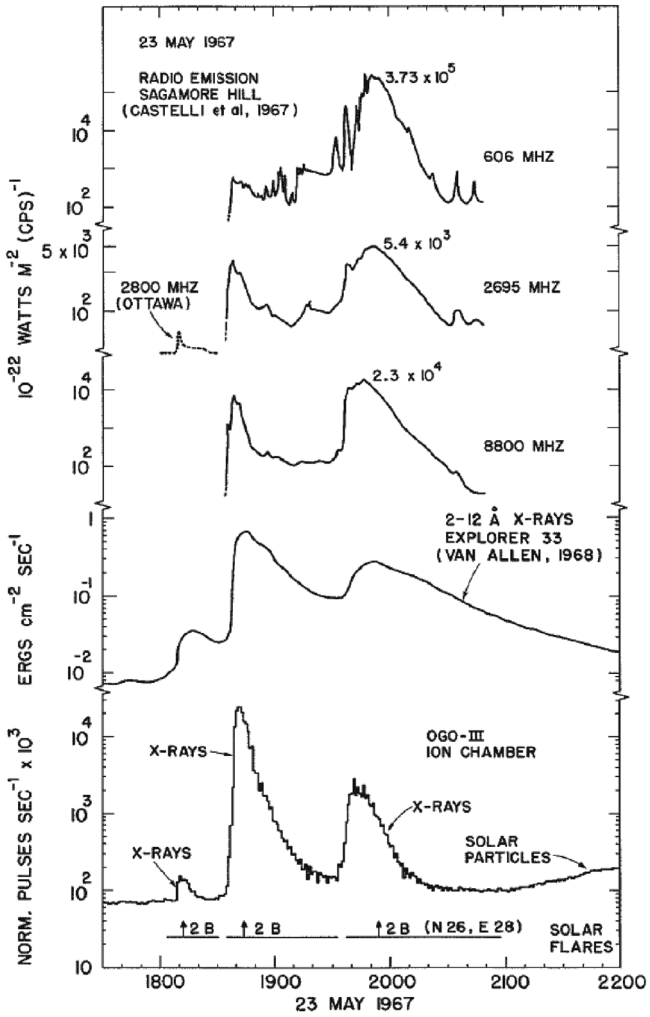

Figure 5. Profiles of solar radio and X-ray emissions on 23 May 1967 from *Kane and Winckler* [1969b]. The interval covers the three primary flares of 23 May 1967. Reprinted with permission from Solar Physics.

[1969] examined the films and reported three enhancements of H α flares at the 3-Brilliant (3B) importance level (areal coverage ranging from 1200 to 1800 millionths of the solar disk) during 1805–2300 UT on 23 May. The two latter flares, occurring within tens of minutes of each other, had a comprehensive flare index (CFI) values of 16. According to *Dodson and Hedeman* [1971], only eight flares exceeding CFI level-15 were recorded from 1955 to 1969; thus, 23 May flares suggested extraordinary solar activity.

The radio portion of the solar spectrum was even more disturbed. *Covington* [1969] designated the radio signature between 1835 and 1935 UT as a "Great Burst" with an F10.7 cm (2800 MHz) peak flux of 8000 solar flux units (sfu) (10^{-22} Wm^{-2} Hz^{-1}). According to data in *Nita et al.* [2002], the probability of a burst exceeding 8000 sfu at frequencies > 2 GHz is ~1% [see also *Nita et al.*, 2004, Figure 3]. *Barron et al.* [1980] show a peak flux of 85100 sfu at 1.415 GHz, which is one of the frequencies used by the current-day GPS. *Castelli et al.* [1968] from the Sagamore Hill radio observatory reported record solar radio bursts at several frequencies with the flare sequence. Peak flux densities exceeded 20,000 sfu at 8800 MHz and reached 373,000 sfu at 606 MHz (Figure 5). The ESSA SDL observation at 184 MHz showed the radio burst as "off the scale" [*Leighton*, 1969].

Castelli et al. [1968] state that "…the first radio burst was small; the third was by far the largest…. The flux densities of the third burst may have been the highest ever recorded in the decimeter portion of the radio spectrum and amongst the largest four in the 8800 MHz region." They further reported that sweep frequency observations from 19 to 39 MHz showed Type IV emission with Type II bursts embedded in the Type IV continuum. *Garriott et al.* [1967] reported compromise of the 137.35 MHz telemetry signal from the ATS 1 geostationary satellite at the same frequency.

Given these data, and even though no direct solar radio observations were being made at 440 MHz, it is virtually certain that extremely high radio flux also occurred at that operating frequency of the DOD's BMEWS.

Although not reported in real time, space-based observations confirmed the intensity of solar activity in other portions of the spectrum. *Van Allen* [1968], using data from an X-ray detector (0.2–1.2 nm) on the Explorer 33 satellite, reported three distinct X-ray flux enhancements during the event (Figure 5). The first flare, an approximate M3-class flare occurred at 18:17 UT [*Van Allen*, 1968]. The second X-ray flare had a flux of 0.65 erg cm^{-2} s^{-1} at 1846 UT (an X6 flare on today's NOAA flare scale). *Kane and Winckler* [1969b] noted similar behavior for the hard X-ray fluxes measured by Orbiting Geophysical Observatory (OGO) 3 satellite. At

1925 UT the neutron monitor onboard a Vela satellite observed an increase in energetic particles, presumably from the 1846 UT flare [*Křivský and Pintér*, 1969] (Note the Vela neutron monitor could not discriminate between high-energy protons and neutrons [*Asbridge*, 2016].). While the effects of the second flare were ongoing, a third flare from the same region produced an X-ray flux of 0.28 erg cm^{-2} s^{-1} at 19:53 UT (*X*2-class flare). A slight increase in energetic protons (>12 MeV) was observed after 21 UT on OGO 3. Figure 5 shows that all of the flares were long duration X-ray events, which were likely associated with CMEs.

The solar flare effects penetrated deeply into the ionosphere [*Mitra*, 1974]. *Křivský and Pintér* [1969] noted solar flare effect (SFE) signals in ground magnetic data in the form of "magnetic crochets." These signals develop in the sunlit sector when flare induced ionization supports excess upper atmosphere currents and attendant magnetic perturbations at the ground. According to *Richmond and Venkateswaran* [1971], the SFE extended across the sunlit sector from San Juan, Puerto Rico to Honolulu, HI, with two distinct phases. The first impulse at 1839:30 UT was the response to EUV photons enhancing the dayside *F* region current system. The longer-lasting variation (> 10 min) peaked at 1847 UT and was the likely signature of anomalous ionospheric *D* region current systems supported by excess X-ray flux.

From the totality of the reports above we can understand that radio communications and radar monitoring during the early to middle afternoon hours (local time) of 23 May in the central U.S. and Canada were subject to significant interference and signal loss. Simultaneously, some of the fixed, high-latitude BMEWS radar faces directly pointed at the setting Sun as it produced record level radio emissions. Even BMEWS faces with non-Sun-directed orientations likely had side and back lobes that were subject to solar RFI.

Other SID effects on radio circuits developed throughout the continental U.S. and the Panama Canal Zone beginning shortly after 1830 UT [*Jean*, 1969]. *Richmond and Venkateswaran* [1971] noted the short wave fade as 3+ (the highest level, due to longevity and depth of fade). Flare effects were evident into the dusk sector, with the ionosonde at Slough Observatory, UK, unable to acquire sounding signals from the ionosphere (M. Hapgood, personal communication, 2016). *Garriott et al*. [1967] reported sudden frequency deviations, and later full signal loss, on the 15 MHz WWV transmission circuit between Fort Collins, CO, and Stanford, CA. The 13 MHz signal used by SDL to monitor for sudden frequency deviations (SFDs) was available during the flare at 1808 UT; however, the signal was lost during the subsequent flares due to ionospheric absorption [*Donnelly*, 1969]. *Thome and Wagner* [1971] noted substantial short-lived electron density enhancements above Arecibo radar with ~300% increase in the *D* region and close to 100% in the *E* region during the 1840 UT flare, and a prolonged 25% enhancement at higher altitudes. They also reported that the Arecibo radar was unable to observe during the third flare due to the flare-related SID. *Garriott et al*. [1969] reanalyzed the ionospheric response to the flares and found that a substantial portion of the flare energy was in the EUV portion of the spectrum, resulting in strongly enhanced and long-lived upper *F* region ionization that extended the solar flare effect. *Mitra* [1974] used these events to explain why the rapid succession of flares with high EUV emissions left the uppermost portion of the *F* region in a state of extended excess ionization. No doubt this partially explains the long-lived dayside radio communication and signal disruptions beyond those caused by the initial radio bursts.

Even with the fading of the third flare, nature was far from finished with communication disruptions. The top row of Figure 3 marks additional Level 2 or greater flares. Just as important the curves and plotted data show the profiles of energetic particle fluxes that set up the next round of solar and geomagnetic torment in the form of PCA events that intermittently shut down most HF radio communications in the polar cap.

The greater than 10 MeV proton flux rose late in the UT day of 23 May (Figure 3). Solar energetic particles pummeled both polar atmospheres, initiating PCA events in the northern hemisphere with onset at 2330 UT on 23 May [*Masley and Goedeke*, 1968; *Cormier*, 1973] and in South Pole Antarctica at 0007 UT on 24 May [*Křivský and Pintér*, 1969]. Significant fluxes of solar protons (tens of MeV) streaming ahead of what was certainly a very energetic CME caused a current-day S1 radiation storm early on 24 May. Figure 3 shows measurements of energetic proton flux in the northern polar cap from Satellite 1963-38C, along with first-light measurements from the Explorer 34 satellite, which launched early on 24 May [*Bostrom et al*., 1969; *Lanzerotti*, 1969a]. The radiation storm surpassed the S2 level by day's end. Radio signaling in the polar caps further deteriorated in the early hours of 24 May [*Masley and Goedeke*, 1968]. The equivalent of a modern day NOAA S-3 radiation storm developed on 25 May. The IMP 4 spacecraft recorded a maximum intensity of 0.75 protons $(cm^2\ s\ sr)^{-1}$ above 94 MeV, with the maximum intensity occurring at 08 UT on 25 May [*Simpson and Fan*, 1973].

10.1002/2016SW001423

Table 1. The 25–27 May 1967 Geomagnetic, Ionospheric, and Atmospheric Effects at 1 AU

Effect	Measurement	References
Ground magnetic and ionosphere severe storm	$Kp = 9$ for 6 h = NOAA G5 class, $Kp \geq 7-$ for 27 continuous hours, top 25 Aa_m* storm; $Aa_m^* = 274$	NASA OMNIweb [*Findlay et al.*, 1969; *Cliver and Svalgaard*, 2004]
Extreme ionospheric storm 25–26 May severe positive-negative phases	100% TEC increase on 25 May due to geomagnetic storm followed by most dominant negative phase in TEC ever recorded	*Webb* [1969], *Low and Roelofs* [1973], and *Mendillo* [2006]
Significant auroral precipitation effects	Scintillation on satellite beacon signal—signal lost early 25 May	*Goodman* [1968]
Hot ionosphere at 1000 km	Electron temperature > 6500 K, extraordinary structuring in electron density and temperature in auroral zone observed by Explorer 22 satellite	*Findlay et al.* [1969]
Aurora at low latitudes 25–26 May	New Mexico 32° north geographic, Alabama; overhead in Washington DC Class II aurora in Devon, UK; off-scale intensity;	*Castelli et al.* [1968], *Findlay et al.* [1969, Figure 1], and *Smith and Webber* [1968, Table 1]
Significant keV auroral proton precipitation 25–26 May	> 35 mW/m^2 during polar pass of satellite OV1-10; 114 kR of emission	*Metzger and Clark* [1971]
Heated thermosphere satellite drag	400 K temperature spike after 6 h, LOGACS apogee decreases by 100 km	*Jacchia* [1969] and *DeVries* [1972]
Geomagnetic micropulsations	"Spasmodic" pulsations of 40 mV/km at 10–20 mHz	*Smith and Webber* [1968]
Coherent global oscillations in VLF emissions	Simultaneous global oscillations at 5−8 kHz, U.S., Europe, and Japan	*Harang* [1968a, 1969]
Plasmapause greatly distorted	Plasmasphere eroded to ~ $L = 2$ complex filamentary structure	*Hayakawa et al.* [1975] and *Grebowsky et al.* [1974]
Dst superstorm, eighth largest 25–26 May	Sudden commencement +55 nT, $Dst = -387$ nT; mean $Dst_{MP} = -230$ nT, very asymmetric ring current	Kyoto *Dst* record [*Balan et al.*, 2016; *Akasofu et al.*, 1969]
Magnetospheric compressions 25–30 May	Sudden Storm Commencements (SSCs) near-equatorial ΔH of 737 nT	*Lindgren* [1968, Figures 6 and 9 and Table IV]
Structuring of solar energetic particle fluxes	Energetic proton enhancements ahead of and at SSC's 24–31 May, IMP 1 and IMP 4	*Lindgren* [1968, Figure 4], *Bostrom et al.* [1969], and *Lanzerotti* [1969a, 1969b]
Magnetopause inside GEO orbit on May 25	> 3 h; 2039–2354 UT ATS 1 geostationary satellite	*Russell* [1976] and *Coleman* [1970]
Semipermanent disturbances in electron and proton radiation belts at $L < 3.5$	Factor of 100 increase in 0.28 MeV electrons at $L = 2.2$, increase of 0.265 MeV protons between $L = 2.25$ and 3.25 on 25 May	*Bostrom et al.* [1970], *Rothwell and Katz* [1973], and *Tomblin and Kreplin* [1970]
Stepped Forbush cosmic ray decrease	11% at Deep River Observatory, Marked north-south asymmetry, Cosmic ray steaming direction reversed 25–31 May	*Harang* [1968b], *Akasofu et al.* [1969, Figure 8], and *Lindgren* [1968]

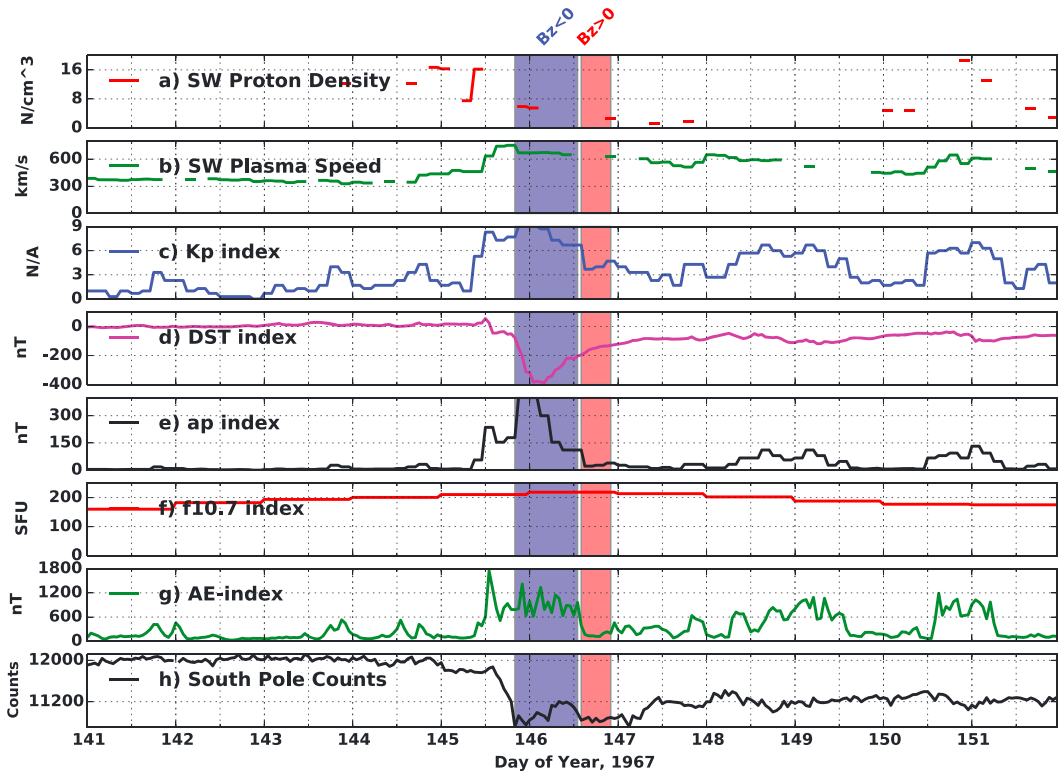

Figure 6. Indices and observations for 21–31 May 1967. (a) Hourly solar wind density and (b) hourly averaged solar wind speed. (c) The 3 h *Kp* index, (d) hourly *Dst* index, (e) 3 h *Ap* index, (f) daily F10.7 cm solar radio flux index, (g) hourly auroral electrojet index, and (h) South Pole neutron monitor station counts. IMF B_z orientations extracted from *Coleman* [1970] and *Williams and Bostrom* [1969].

2.3. Subsequent Geomagnetic Activity and Radio Propagation Effects

The May 1967 storm was an overlapping sequence of solar events causing subsequent radiation, magnetic, and ionospheric storms, which occasionally superimposed in their effects on the geospace environment. Stress on command, control, and communication systems continued beyond that created by the historic radio bursts. Table 1 and Figure 6 summarize the geomagnetic storm effects of the late May activity [see also *Akasofu et al.*, 1969]. Inspection of Figure 6 shows that the hourly average of solar wind density ahead of the first disturbance (Figure 5a) was ~15 particles/cm^3, consistent with a high-density sheath ahead of the ejecta. *Lindgren* [1968] estimated a 40 h Sun-Earth transit time for the event associated with the 23 May, 1845 UT flare, and a 41 h transit time for the 23 May 1946 UT flare. The near-tandem arrival of these structures was likely important in the subsequent storm energetics. The wave of solar energetic particles peaked at Earth orbit with a classic sharp rise and geomagnetic SC associated with arrival of the first shock at 1021 UT on 25 May. A second SC, measured by extraordinary number of ground station (45) at 1235 UT and accompanied by rising solar wind speeds (Figure 6b), initiated the eighth largest *Dst* storm on record. The second SC was followed immediately by the largest auroral electrojet excursion of the interval (Figure 6g) and by excitation of a 114 kR hydrogen Lyman alpha aurora observed by satellite OVI-10 (1966-111B) during its Northern Hemisphere pass prior to 1300 UT. *Metzger and Clark* [1971] estimated $>$ 35 mW/m^2 of auroral proton energy (keV) deposition with the UV proton aurora. They also reported satellite-to-ground-link disturbances due to the active ionosphere. The H α auroral emission remained well above background through 26 May 1967.

By 2030 UT on 25 May the ATS 1 geostationary satellite was in the dayside postnoon magnetosheath and remained so for more than 3 h [*Russell*, 1976]. Although magnetopause crossings occur about once a month averaged over the solar cycle [*Dmitriev et al.*, 2004], magnetopause crossings in the postnoon sector are less frequent, and events with durations of more than an hour constitute less than one third of the observations. Thus, a 3 hour-long magnetosheath visit by ATS 1 suggests a severe magnetopause distortion. The onboard magnetometer measured magnetosheath (shocked) southward magnetic field of −160 nT [*Coleman*, 1970].

A back-of-the-envelope estimate, accounting for factor of 4 shock enhancement of the magnetic field, suggests that the interplanetary magnetic field (IMF) vertical (B_z) component was in the vicinity of −40 nT. The *Dst* versus B_z south plot in *Vichare et al*. [2005] indicates that the value was likely closer to −50 nT. Figure 2 of *Williams and Bostrom* [1969] shows the IMF was southward through ~12 UT on 26 May.

The 26 May 1100 UT SDFC report (copied below) succinctly captures the solar-terrestrial mayhem. See supporting information file for additional bulletins.

NNNNUUV
PP KGFF
DE BOU 261100Z
FROM SPACE DISTURBANCE FORECAST CENTER ESSA BOULDER COLO,
SPACE DISTURBANCE FORECAST NUM1BER 540D ISSUED 1100 Z
MAY 26 1967
THE PROTON EVENT CONTINUES, AS WELL AS THE VERY SEVERE
MAGNETIC STORM. DURING THE NEXT 12 HOURS, MAJOR FLARES
ARE LIKELY.
THE IMPORTANCE TWO NORMAL FLARE AT 26/0205Z HAS BEEN
RECLASSIFIED AS IMPORTANCE THREE NORMAL. THE FLARE DID NOT' OCCUR WITHIN.
THE MAJOR DELTA CONFIGURATION BUT MAY ADD TO THE PRESENT PROTON EVENT.
AURORA IS REPORTED AS FAR SOUTH AS NEW MEXICO.
BT

Data in Figure 6 show that the full force of the geomagnetic storm developed in stages, with the exceptional *Dst* downturn beginning in the later UT hours of 25 May. This timing is consistent with the ATS 1 geostationary measurement of the 160 nT southward magnetosheath fields beginning at ~ 20 UT. Geomagnetic storm effects were impressive (Table 1), with aurora observed in central Europe and in the southern U.S. [*Findlay et al*., 1969]. They also reported extraordinary electron temperatures and densities in the auroral zone. *Jacchia* [1969] used satellite drag measurements from six spacecraft at altitudes ranging from 338 to 1001 km to infer a global neutral atmosphere temperature increase (spike) of 400-500 K that lagged storm onset by ~6.5 h. In an amazing coincidence the U.S. Air Force had launched the then-classified Low-G Accelerometer Calibration System (LOGACS) on an Agena satellite into a near-polar low Earth orbit on 22 May 1967. The accelerometer remained in orbit through 26 May providing the first expanded view of neutral winds and density perturbations over the altitude range of 140–400 km during an extreme storm [*DeVries*, 1972; *Bruce*, 1972]. LOGACS revealed deep neutral density bulges and troughs as well as >1500 m/s neutral winds during the storm main phase. From 22 to 26 May the satellite apogee decayed by more than 100 km from 403 km to 296 km. *DeVries* [1972] argued that the data also supported the idea of Joule-heating-driven neutral density waves, which is consistent with the idea of ionospheric gravity waves proposed by *Hines* [1960], although the neutral density wave idea was not without controversy [*Allan and Cook*, 1974]. These experiments helped explain the satellite tracking difficulties experienced by NORAD during the late May 1967 storm (L. Snyder, personal communication, 2016).

The Naval Research Laboratory reported loss of signal between the ground and a satellite beacon during the height of the geomagnetic disturbances [*Goodman*, 1968]. This situation likely developed from a superposition of ionospheric storm effects and ongoing solar disturbances in the VHF/UHF bands. The Trieste Astronomical Observatory reported saturation of its 239 MHz system radio system due to extreme solar flux at that frequency on 25 May 1967 [*Abriami and Zlobec*, 1968]. Solar disturbances in the VHF band are known to increase as active regions reach solar central meridian. On 25 May McMath Region 8818 was so positioned.

Global, coherent very low frequency oscillations developed shortly after 21 UT and extended to low latitudes [*Harang*, 1968a, 1969]. The plasmapause eroded to within 2 R_E [*Hayakawa et al*., 1975; *Grebowsky et al*., 1974]. During the same time proton and electron fluxes in the inner radiation belts were undergoing modification [*Bostrom et al*., 1970; *Rothwell and Katz*, 1973]. Further, *Mendillo* [2006] remarked that the most prominent negative phase (reduction) in total electron content (TEC) ever reported occurred on 26 May. For brevity additional geomagnetic storm effects are tabulated in Table 1.

There is an additional interesting aspect of the likely tandem-CME arrival that drove the *Dst* superstorm. *Lugaz and Farrugia* [2014] report that interacting CMEs may combine to produce large IMF events with deep depression of *Dst* and a propensity for sawtooth oscillations of the geomagnetic field. We have not been able to determine if the ATS 1 data can provide confirmation of these oscillations; however, the *AE* index record in Figure 6g strongly suggests rhythmic global field oscillations consistent with a sawtooth event.

Even as Earth recovered from the violent 25–26 May geomagnetic storm, McMath Region 8188 flares and emissions continued. These likely added to energetic particles fluxes already present at Earth, thus extending the ongoing PCA event and maintaining the radiation storm level at today's S1 level for a full week. A second triple eruption from Region 8818 started at 0546 UT on 28 May. This flare was reported at N28, W32, an ideal location for energetic particle access to Earth. Figure 3 shows that while the most energetic particles arrived first, nearly all channels recorded dramatic increases of energetic proton flux in only minutes, resulting in another S3 radiation storm. *Lanzerotti* [1969b] argued that this sharp enhancement was the result of a combination of solar wind structuring from multiple incoming shocks, a possible sector boundary crossing, and the flare-associated protons.

The interplanetary disturbance(s) from the 25–26 May flares arrived on 28 May producing SCs and generating a strong geomagnetic storm with maximum $Kp = 7$ and 12 h of moderate storming, G2, $Kp = 6$, conditions. The geomagnetic disturbance from the 28 May flare likely reached Earth at midday on 30 May [*Lindgren*, 1968, Table IV] creating a sudden impulse but not a geomagnetic storm.

The extended Forbush decrease shown in the South Pole neutron monitor data (Figure 6h) gives a general sense of the magnitude of heliospheric disturbance produced by the series of combined shocks and CMEs. Only in early June did Earth exit the cosmic ray shadow (Forbush decrease) generated by the merged structures [*Carmichael and Steljes*, 1969]. The inner radiation belts disturbances linked to these storms lasted for months [*Bostrom et al.*, 1970; *Rothwell and Katz*, 1973; *Tomblin and Kreplin*, 1970].

2.4. How Severe Were the May 1967 Storms?

Clearly, the May 1967 event was a superposition of solar, magnetospheric, and ionospheric storms. How should we categorize these? The radio bursts accompanying and following the white-light flare on 23 May were designated as "Great Bursts" [*Castelli et al.*, 1968]. In particular, those authors reported an extraordinary burst of 373,000 solar flux units at 606 MHz, which was the largest, observed as of that date. *Klobuchar et al.* [1999] listed the 23 May event as the top SRB at 1.4 GHz (current GPS L1 frequency). Note that the December 2006 event discussed in *Cerruti et al.* [2006] is now recognized as the top SRB event at the L1 frequency with a burst $>$1,000,000 sfu. With regard to ionospheric disruptions, the May 1967 events were at or near the top of the list. *Mitra* [1974, chap. 6] categorizes the solar flare event as "outstanding", noting that the SFD was, at the time, the largest observed at Boulder, CO, USA, since Boulder started measuring SFDs. Mitra further used the 21 and 23 May events as examples of extraordinary ionospheric behavior throughout his text. In a review of ionospheric storms *Mendillo* [2006] remarked that the 25–26 May ionospheric positive-negative storm was "extreme" with the negative phase being the largest on record. As far as sustained disturbances across many facets of the ionosphere, especially in the polar cap, the storm ranks high. Yet the storm defies easy categorization. Radio bursts do not have a scale, primarily because interference is so system specific. For similar reasons ionospheric disturbances are without a widely accepted scale.

On the NOAA geomagnetic storm scale, the event was a G5 (extreme) storm—a level of storm that would be expected about 4 times per solar cycle—thus a likely top 20 level storm in the last four solar cycles. In terms of X-ray output, and solar radiation, the storm reached R3 and S3 levels (strong). The longevity of the excess EUV emissions were most likely extreme based on descriptions in the previous section, but again, there does not seem to be a benchmark for this.

As a magnetospheric disturbance, the 25–26 May event ranks near the top in the record books. With *Dst* value of -387 nT, *Cliver and Svalgaard* [2004] rate the storm in the "top 10" of all events since 1932. In their Figure 4 plot of the Aa_m* versus *Dst* indices, the event appears to be in lower left, thus in the top 10 of extreme events. *Balan et al.* [2016] considered the average main phase value of *Dst*, called Dst_{MP}, and also put the 25–26 May event in the top 10. There were likely large rhythmic oscillations in the geomagnetic field based on a number

of indicators; however, a scale for these does not exist. The magnetopause was within geosynchronous orbit for at least 3 h before the only orbiting geostationary satellite reentered the postnoon magnetosphere. Nonetheless, the storm did not have the combination of solar wind speed and southward IMF needed to meet the impulsiveness criteria for severe storm classification given by *Balan et al*. [2015]—the arrival speed was apparently too low. Consistent with this, no records of significant GICs have been found. The aurora was observed near the southern U.S. border (latitude of 32° geographic [*Castelli et al*., 1968]) and in central Europe—falling far short of the great low latitude auroral events of the 1800s.

Beyond the scales, indices, adjectives, and numerics used in most comparative storm studies, there are less tangible factors that make this space weather storm unique. The geomagnetic effects and radio absorption events were consistent with expectations for strong to extreme storming; however, these effects were compounded by the superposition of effects and by the extraordinary radio burst, which caused the "drastic impacts… to NORAD's early warning systems." We argue that these additive effects and the repercussions of this storm push the May 1967 storm into the historically "Great" category, similar to those listed in *Hapgood* [2010].

3. Discussion: Storm Impacts and Legacies

3.1. May 1967 Storm Impacts: Radio Frequency Interference and Space Weather Support

Returning now to the effects of the solar radio bursts, the BMEWS was a multisite and multiantenna radar system operating at 440 MHz at sites in Alaska, USA; Thule, Greenland; and Yorkshire, England. Basic Sun angle calculations indicate that the setting, and very active Sun, was "visible" to all of the BMEWS radars late in the UT day on 23 May, with the Thule radar particularly well aligned. Although not overtly stated by *Citrone* [1995], authors of this manuscript present for the event or involved in the postevent analysis attest that many of the "impacts" were from the record SRBs. Such an intense, never-before-observed solar radio burst was interpreted as jamming. (Recall that a similar situation occurred in the early days of radar development in World War II when "enemy jamming" turned out to be solar RFI [*Hey*, 1946].) Cold War military commanders viewed full scale jamming of surveillance sensors as a potential act of war. While no detail of the nature of the "incident" is provided in *Citrone* [1995], the online memorial tributes to Col C. K. Anderson, on the occasion of his passing in late 2015, clearly credit him and his NORAD solar forecasting staff (in particular Major Donald Sherry and Captain Lee Snyder) with providing the information that eventually calmed nerves and allowed aircraft engines to cool as they returned to normal alert stance. With the limited data available at the time, AWS solar forecasters were able to extract sufficient information from AFCRL solar observations to convince high-level decision makers at NORAD that the Sun was a likely culprit in contaminating the BMEWs radar signals. Thus, it appears that unlike some of the human-error and miscommunication events in the 1970s [*Forden*, 2001], bombers did not take to the skies but were nonetheless positioned to do so.

While it may seem curious to place so much emphasis on a "hold the aircraft" decision, it is well worth noting that during the politically tense days of late May 1967 a full out aircraft launch by western forces could have been very provocative and, just as importantly, difficult (if not impossible) to recall in the greatly challenged HF-UHF radio environment. SAC crews were trained to "complete the mission" unless clearly recalled (see discussion at George Washington University's National Security Archive page: http://nsarchive.gwu.edu/nukevault/ebb304/). Since the decision chain for responding to the early warning system incident went to the "highest levels of government," it is likely that the timely information about the space environment, provided first to NORAD (and ultimately to SAC and the Pentagon), turned a grave situation into a manageable one.

We do not know if the May 1967 event was the first of its kind in the modern era (although it seems likely); we do know from entries in the online history of Air Weather Service that space environment/weather has been and continues to be monitored for its role in technology and communication anomalies:

> "**6 – 20 Mar** (1989) Period of strong solar activity caused an uncommon Polar Cap Absorption event that crippled High Frequency (HF) communications, caused interference and high noise levels for Very High Frequencies (VHF), degraded radar performance, caused satellite communications problems, enhanced satellite charging, (caused) satellite tracking, and compass alignment problems."

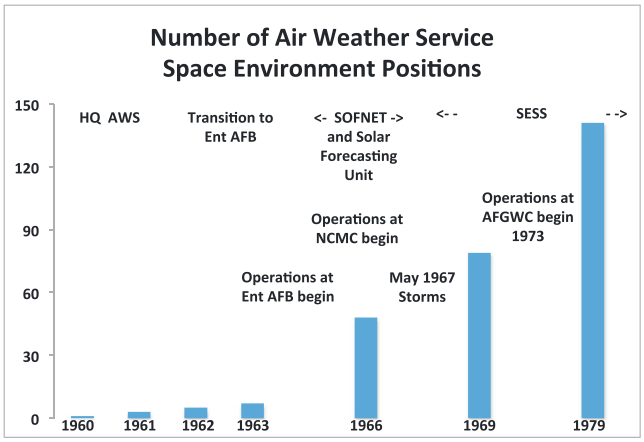

Figure 7. Number of active duty AWS Space Environment Support Positions. These numbers are taken from historical reports and rosters as well as the online AWS history. Values have an uncertainty of about 20% given that military members were often reassigned on short notice and some performed both SESS and non-SESS duties.

"**15 Jul 2002** Space weather forecasters, from the recently activated AFWA Space Weather Operations Center (SPACEWOC), issued their first event-level warning to the 614th Space Operations Group based on an observed solar flare. At 15/1959Z, the sun in region 0030 produced a flare that reached X3.0 category in x-rays and had several event-level radio bursts shortly after that time. A (NORAD) Command radar site confirmed it had 'painted multiple inbounds.'"

(Note: The reference to "region 0030" is to NOAA AR 10030 and "multiple inbounds" relates to the NORAD radar producing a false detection of incoming targets due to RFI.)

"**6-7 & 14 Dec (2006)** AFWA (Air Force Weather Agency) space weather operations noted two significant solar events. On 6-7 December, space weather operators noted two M flares and an X6.5 X-Ray flare. The X6.5 flare produced significant radio bursts, a proton event, and a geomagnetic storm. Five moderate to severe unclassified impacts to communications were reported and one impact was reported to an unclassified radar site…."

Beyond impacts on DOD systems the May 1967 events provide a data point for current-day cell phone communication and navigation vulnerabilities. *Gary et al*. [2005] note that a cell phone base station may experience enhanced noise during SRB's. Bursts exceeding ~1000 sfu "may begin to cause problems for the system if the horizon-looking antennas are pointed at the rising or setting Sun." They further state that bursts with an order of magnitude more flux are likely to be more disruptive. The 23 May 1967 radio burst may have been quite disruptive at base station frequencies. *Cerruti et al*. [2006] have expressed similar concerns about sensitivities of GNSS signals to extreme radio bursts. While the May 1967 radio fluxes reported near the current-day GPS L1/L2 frequencies were likely not sufficient to cause significant GPS disruption had the system existed, the fluxes during the 6 December 2006 event clearly crossed the disruption threshold.

3.2. Legacy: U.S. Air Force Space Environment Support System

Citrone [1995] attributes the larger role of AWS Space Environment personnel in AF decision making to the May 1967 "incident." Within months of the May 1967 storms a formal AWS ionospheric section began supporting ionospheric-dependent systems, with the first supported operational system being the 440 L over-the-horizon radar operating over the Eurasian continent [*Townsend et al*., 1982]. In late 1968 AWS unveiled a Space Environment Support System (SESS) organization plan, which consolidated several space monitoring systems, including SOFNET. SESS efforts targeted required operational capabilities in ionospheric, neutral density, and radiation effects, as well as support to NORAD. By 1969 the ionospheric forecasting effort expanded to a 24 h operation. This effort was so computer intensive that SESS Forecast Center moved to Air Force Global Weather Central (AFGWC) at Offutt AFB in 1973 to use increased computer power available there, with a by-product being closer alignment with SAC. In 1972 NOAA and AWS agreed that cooperative efforts in space environment forecasting would be mutually beneficial [*Poppe*, 2006, chap. 8], thus began a longstanding partnership that extends to present day.

We will not revisit here the intricacies of SESS program development since a richer history of SESS can be gleaned from various entries in *Townsend et al*. [1982], and the online history of AWS: http://

www.557weatherwing.af.mil/shared/media/document/AFD-131104-184.pdf and the brief discussion in section 5.4.11 of *Goodman* [2005]. Rather, we highlight some aspects of SESS-related activities that have had long-term impacts: the growth of SESS as an enterprise within AWS, the AF solar monitoring program, Education and Training, Scientific Investigations, and the Defense Meteorological Satellite Program. Each of these is worthy of a separate historical manuscript.

3.2.1. Growth of SESS

Figure 7 provides a sense of the growth in active duty staffing for space environment support as an enterprise within AF. The first significant increase in staffing was the result of initiating SOFNET and establishing the Solar Forecast Unit in NCMC. A second large delta followed in 1968–1969 as AWS created a broader and more formal space environment support system, SESS, for DOD at large. As indicated by *Citrone* [1995], and consistent with the memories of several authors of this manuscript, the May 1967 storm was a catalyst for SESS growth after the storm impacts received significant attention at the Pentagon. Developing DOD reliance on space assets sustained the momentum.

3.2.2. Solar Electro-Optical Network

The expansion of Solar Electro-Optical Network (SEON) is perhaps the most tangible hardware legacy of events in the 1960s. After USAF's Sacramento Peak Observatory started daily flare patrols in 1951, the value of the observations became clear. From the early 1960s solar observatories provided input to real-time military and civilian space weather watches, warnings, and alerts. In 1969 AF solar observers were operating out of Tehran, Iran; Athens, Greece; Manila, Philippines; and four U.S. locations. Four overseas and North American ESSA solar observatories sometime filled in gaps. USAF solar observatories have maintained eyes on the Sun through the decades [e.g., *Castelli et al*., 1973; *Fitts and Loftin*, 1993]. The current-day AF solar observing network operates optical (O) and radio (R) instruments at five sites: Learmonth, Australia (O and R); San Vito, Italy (O and R); Sagamore Hill, MA (R); Kaena Point, HI (R); and Holloman AFB, NM (O). Optical sites provide data on sunspots, flares, filaments, and magnetic field configuration. Radio sites monitor the radio interference and emissions at discrete frequencies (15400, 8800, 4995, 2695, 1415, 610, 410, and 245 MHz). Additionally, radio spectrographs sweep their observations between 25 and 75 MHz and 75 and 180 MHz to search for signals of moving transients in the solar atmosphere (557th Weather Wing, http://www.557weatherwing.af.mil/library/factsheets/factsheet.asp?id=222254 and http://www.557weatherwing.af.mil/library/factsheets/factsheet.asp?id=22225, both accessed on May 1 2016, http://www.557weatherwing.af.mil/shared/media/document/AFD-131104-184.pdf).

3.2.3. Education and Training

A long-lived SESS educational program developed, with hundreds of AWS personal earning advanced degrees and/or attending intense space environment short courses. After retirement many of these soldier-scientists moved into influential civilian industry and academic careers. As AFCRL became the Air Force Geophysics Laboratory (AFGL) interest in the space environment grew to the point that AFGL published the now widely used Handbook of Geophysics and the Space Environment [*Jursa*, 1985]. This 25-chapter monograph provided an encyclopedic summary of what was known about the space environment and its interactions with the atmosphere.

3.2.4. Scientific Investigations

Operational needs generated numerous scientific studies, some of which were performed by groups within AFCRL. Two of the most long-lived efforts were for prediction of energetic protons and satellite drag. Development of the Proton Prediction System spanned decades [*Smart and Shea*, 1979]. Other studies were contracted or granted to civilian universities and businesses, in particular the Parameterized Real Time Ionospheric Specification Model and the Magnetospheric Specification Model. *Oder et al*. [2004] chronicle the AFCRL and AFGL support for SESS (and include a brief mention of the May 1967 event). The Air Force Office of Scientific Research became a leading funder of SESS-related research and today continues to fund research efforts in satellite drag prediction.

3.2.5. Defense Meteorological Satellite Program

Defense Meteorological Satellite Program (DMSP) developed as a classified weather project in the early 1960s [*Fuller*, 1990 and *Hall*, 2001] and was declassified in the mid-1970s. In 1970 AFCRL initiated a research program to correlate DMSP auroral photographs with the actual structures of the polar ionosphere. USAF has provided nearly 100 satellite years of particle and upper atmosphere state data to the archives of NOAA's NCEI STP. These DMSP data have contributed to thousands of space-related scientific studies worldwide.

The long-term military impacts of this storm were significant and perhaps unequaled. The May 1967 storm(s) brought about sustained changes in the way the U.S. Air Force (and DOD) viewed the space environment, allowing investments in monitoring equipment and forecasting systems that have paralleled, and to some degree provided a foundation for, similar civilian activities. As far as long-term societal impacts, we are all left to think about how the outcomes of the 23 May 1967 solar radio storms could have been different in the absence of trained and astute AWS solar observers/forecasters who provided crucial information that reached decisions makers at the highest levels of government.

4. Conclusions

We have provided a broad perspective of the space weather impacts associated with the late May 1967 solar radio bursts, flares, energetic particles, and coronal mass ejections from McMath Region 8818. Impacts on the important technology systems of the day reached critical levels. The May 1967 event was long lasting with a series of events following McMath Region 8818 across the disk of the Sun. The largest solar radio burst of the twentieth century (at specific frequencies) produced 373,000 sfu at 606 MHz. The F10.7 cm flux rose briefly to 8000 sfu. Military radio technologies were severely impacted by (1) solar radio bursts, (2) solar energetic particle deposition, and (3) general disruption of ionospheric radio and ground-to-satellite communication channels. The magnetosphere was in a near-record state as measured by the *Dst* index and many other parameters. Satellite drag effects were demonstrated and quantified. The polar cap experienced ongoing communication outages for over a week. The near-Earth inner heliosphere was in a cosmic ray shadow (i.e., Forbush decrease) for more than 2 weeks. Inner radiation belt variations in electron content were still being measured months after the driver event. From the perspective of the authors of this manuscript, some of whom had close knowledge of the event (s), the role of Air Force SESS personnel was critical in maintaining the well-being of the nation and the world as the May 1967 storm unfolded. Further, the May 1967 space weather events created a cascade of important decisions and studies that have contributed to the field of Space Weather as we know it, thus providing information to system engineers, and decision and policy makers at many levels, even today.

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