

# Recognizing Geomagnetic Storms in Marine Magnetometer Data: Toward Improved Archaeological Resource Identification Practices

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**Abstract** Strong magnetic field perturbations resulting from Earth-directed solar events, collectively referred to as geomagnetic storms, can adversely affect many aspects of marine archaeological survey. The immediate onset of geomagnetic storms and the fast compression of the magnetopause creates a short-duration, high amplitude spike in Earth's magnetic field that appears similar to the signature of an archaeological anomaly. Aggressive processing, analysis, and comparison of single instrument, total field marine magnetometer survey and observatory datasets collected during geomagnetic storms on days of Kp 5 or greater resulted in no demonstrable ability to isolate and remove the storm sudden onset signature. Of the 34 storms analyzed, 34 possessed onset signatures that were considered to be potentially misleading, resulting in possible aliasing of temporal variation (the storm sudden onset signature) for spatial variation (archaeological anomalies of interest). Based on a 95% confidence level, it is estimated that 89.7 to 100 percent of geomagnetic storms occurring on days of Kp 5 or greater will generate signatures that may be misinterpreted as archaeological sites. Recommendations are made for marine magnetic data collection and processing methods that may adequately account for geomagnetic storms, allowing for improved precision in analytical interpretation and thus improved management of archaeological resources.

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## 1.0 Introduction

Magnetic field perturbations resulting from Earth-directed solar events, collectively referred to as geomagnetic storms, can affect many components of maritime operations. For marine archaeologists, these storms can introduce noise on remote sensing instruments, interfere with global positioning system-based navigation, and mask spatial variation in Earth's magnetic field. This study focuses on the latter impact as it pertains to the identification of archaeological resources located on submerged Federal lands of the US outer continental shelf, but the implications are broadly applicable.

Geomagnetic storms of sufficient intensity to be disruptive (Kp >5) occur in average frequency of 2,604 storm events per eleven-year solar cycle over the course of 1,454 storm days (US Dept. of Commerce 2014c). Kp refers to Kp index, or *Planetarische*

*Kennziffer*, a value that measures the three-hour magnetic field variation from thirteen sub-auroral magnetic observatories around the world on a quasi-logarithmic scale from 0–9 (Maus et al 2010); the greater the Kp, the more perturbed Earth's magnetic field. This equates to sensed effects of magnetic field perturbations in survey data on an average of 36% of days, with more occurring during solar maximum and fewer occurring during solar minimum. Given the regularity of these perturbations, for effective identification of archaeological anomalies, either survey methods or processing techniques must remove temporal variations in the magnetic field in order to allow spatial variation to be clearly assessed and analyzed.

Data were obtained to test the hypothesis that neither the current sampling methods using a single, total field magnetometer with no base station, nor the current processing methods regularly applied to marine magnetic survey data adequately remove this

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temporal variation and isolate the spatial variation for analysis and assessment. Inaccuracy of this kind could result in small archaeological anomalies missed through removal during data processing, or false positives retained as archaeological targets when the signals observed are, in actuality, caused by geomagnetic storms. The broader impacts may include buried archaeological sites destroyed because over-processed data removed their signatures and prevented their identification, or much needed offshore energy developments curtailed to protect areas that are not actually archaeologically-sensitive.

Sections 2, 3, and 4 provide background on magnetic theory and magnetometers, survey methods and processing techniques typical to marine archaeology, and sources of variation to Earth's magnetic field, respectively. Section 5 presents objectives and methods of the study and Section 6 presents study results. The paper concludes in Section 7 with recommendations for data collection and processing methods that may adequately account for geomagnetic storms.

## 2.0 Magnetic Theory and Magnetometers

Magnetometers sample the amplitude of Earth's magnetic field at a precise location and time. For archaeological purposes, actual absolute magnetic field values are irrelevant; rather, it is amplitude variation in a particular spatial location that is of interest to the archaeologist. This is because ferromagnetic objects - specifically ferromagnetic *archaeological* objects - alter the magnitude of Earth's magnetic field (Bevan 1999). Ferromagnetic objects attract lines of flux, increasing the magnitude of the field in the area immediately surrounding the object, and subsequently repel them, decreasing the magnitude of the field in areas spatially further from the object. In other words, the object behaves as a dipole (Bevan 2006; Breiner 1999; Blackley 1996; Aitken 1974). This variation signature is referred to as an 'anomaly' in magnetometer data. The magnitude of the variation is a function both of the amount of ferromagnetic material as well as the distance between the magnetometer and the anomaly source (Breiner 1999; Smekalova, Voss, and Smekalov 2008; Bevan 2006).

There exist two classes of magnetometers that differ primarily in their manner of measuring Earth's magnetic field: total field and vector magnetometers. Vector magnetometers require extreme stability to operate accurately; thus, major difficulties arise in applying this technology to marine archaeology where excessive wave motion undermines stability. (Allred 1964; Korenaga 1995; Hrvoic 2007). For this reason, vector magnetometers are rarely used in marine survey (Camidge et al 2010) and are not considered further in this study. The remainder of this discussion refers only to total field magnetometers, which are principally used for marine archaeology.

Total field magnetometers can be operated as either a single instrument that measures the total field at any single place and time, or as a gradiometer, which measures the change in magnetic field over a distance traversed. In single instrument configuration, only one instrument is moved about the survey area to sample the magnetic field (expressed in nanotesla [nT]). In gradiometer configuration, two or more sensors are arranged in parallel with one another and both are simultaneously moved about the survey area; the difference in readings between sensors is calculated (expressed in nT/meter[m]; Bevan 2006). The application of total field magnetometers to marine archaeology, both in single instrument and gradiometer configuration, is discussed below.

## 3.0 Magnetometer Survey and Processing Methods Typical of Marine Archaeology

Data collection methods utilized in marine environments are complicated by many factors that introduce imprecision and result in reduced ability to sense small archaeological resources. Whereas archaeological anomalies on terrestrial sites in North America are measured in fractions of nT (Kvamme 2006a; Weymouth and Nickel 1977; Jones and Munson 2005), the smallest change reliably detectable in oceanic environments is reported to be 5 nT, although in some cases, anomalies of 2–3 nT may be identified (Camidge et al 2010). The detectability of anomalies is a function of multiple factors, including number of samples per spatial extent; vessel speed; shape and magnetic moment of ferromagnetic material; distance of sensor to sensed object; and sea state. To sense anomalies of this size in the marine environment using currently-available equipment requires a consistent vessel speed of ~5 knots, calm sea state, and operation of the sensor at <6 m altitude from the sea floor in parallel survey lanes spaced no greater (and preferably much less) than 30 m apart. Precision in marine magnetometry is of extreme importance because the magnetometer remains the best technology available and, in some environments, the only technology available, for identifying shallowly-buried submerged archaeological resources; maintaining a <6 m altitude improves the likelihood that the instrument will sense buried sites.

The following section briefly summarizes survey and processing methods typical to marine archaeology and illustrates how temporal variation in the magnetic field may not be adequately resolved. Detailed background information on the theory and practice of magnetometry for marine archaeology is presented in Hall 1966; Wald and Cooper 1989; Verboom et al 2000; Breiner 2009; Cambridge et al 2010; and Bright, Conlin and Wall 2014.

### 3.1 Marine Data Acquisition Methods

One or more magnetometers are placed in a rigid towfish body and towed very near to the seafloor at an extended distance of at least three times the vessel length behind the survey vessel in order to isolate the vessel's influence on the magnetic field from the measurements being collected by the instrument(s) (Verboom et al 2000). As the vessel traverses a set of parallel survey lines throughout the survey area, the instrument records the value of Earth's magnetic field; the measured value represents the sum total of all contributors to the magnetic field at that place, in that moment.

Before marine magnetic data may be used to identify archaeological resources, all temporal variations must be eliminated from the collected data (Wald and Cooper 1989). Weymouth and Huggins wrote "some method must be used to correct for the temporal variations in the Earth's field. Without such corrections, the resulting magnetic map will be distorted and spurious anomalies will appear" (1985, 198). These statements do not suggest a simple solution, however.

Wald and Cooper (1989) illustrated the difficulties inherent in resolving temporal variation in Earth's magnetic field from marine survey data; multiple examples demonstrated that allowing temporal variation to remain can lead to an inaccurate interpretation, including masking small amplitude spatial anomalies. The temporal variations in these examples are not large (10–30 nT), but they are quite sufficient to mask archaeological signatures of interest (Bright, Conlin and Wall 2014). Considering many geomagnetic storm-induced temporal variations approach 1000 nT (see below), the possibilities for inaccurate interpretation grow considerably. Bevan also illustrated this point; magnetic surveys conducted without the ability to resolve the temporal field result in distorted anomalies, with correction ranging from complex to impossible (2006).

### 3.2 Methods for Resolving Temporal Variation in Marine Survey Datasets: Theory and Practice

Two primary methods exist for effective resolution of temporal variation in marine magnetometry data; both are associated with data acquisition practices as opposed to post-acquisition processing methods. Wald and Cooper proposed either the use of a base station or the application of multiple magnetometers in gradiometer configuration to "unequivocally demonstrate that coincidental time variations are not responsible for particular magnetic anomalies" (1989, 25). Camidge et al (2010) echoed these sentiments, recommending the positioning of a base station as close to the survey area as possible, or use of a gradiometer for effective removal of temporal variation.

Several advantages are conferred by use of a gradiometer: greater spatial resolution of buried features

and accentuation of nearby or shallow features (Bevan 2006; Breiner 1999; Henson 2006; Wald and Cooper 1989); effective resolution of the shape of anomalies (Wald and Cooper 1989); and highly effective removal of temporal variations of the magnetic field (Breiner 1999; Tchernychev, Johnston and Johnson 2007a and b). Because the two instruments are operated within 0.5 m of one another and the total field is sampled simultaneously, any difference in readings is clearly attributable to spatial variation. However, it is operationally difficult and far more costly to deploy a gradiometer (Tchernychev, Johnston and Johnson 2007a and b).

The infrequent application of gradiometers in the marine environment (Camidge et al 2010) led Plets, Dix and Bates to call for more data before endorsing them (2013). However, initial experimentation by Wald and Cooper (1989) has been supplemented by more recent efforts to address tow orientation and processing complications (Tchernychev, Johnston and Johnson 2007a and b; Johnson 2009; Marine Magnetics 2012a and b). Verboom et al reported precise measurement with a "stable, highly controllable transverse gradiometer" (2000, 2). The expense of multiple instruments as opposed to a single instrument, however, remains an impediment, regardless of the advantageousness of higher accuracy conferred by the gradiometer configuration.

Although fairly common in nearshore archaeology, base stations are rarely employed for offshore surveys. An untested argument exists that the large distance between offshore survey areas and any shore-located base station (e.g.  $\sim$  <200 nautical miles) renders them useless, not to mention expensive. Another untested argument seems to doubt the technical feasibility of placing a base station near a survey area in the offshore environment. Certainly no published evidence demonstrates a failed attempt at placing and using an offshore base station (cf Boyce et al 2004, Taylor 1993, Hrvoic 2007; Eittreim et al 1986 for theoretical and applied use of a base station).

Given the additional cost, inconvenience, and lack of agreement on the necessity of using a base station or gradiometer, the default methodological approach for marine archaeological survey has been to collect magnetic data using a single instrument, total field magnetometer with no base station. The assumption is made that contouring single instrument data in plan view will indicate an anomaly in the same general area on several adjacent survey lines, which is true, but only if the spatial anomaly is sufficiently large to be sensed on adjacent lines. Presence on multiple lines would clearly indicate spatial variation as opposed to variation arising from an external source. However, it may also *not* do so if the spatial anomaly is too small to be sensed on adjacent lines (cf Bright, Conlin, and Wall 2014). Therefore, presence or absence of anomalies on adjacent survey lines will not ensure confidence in distinguishing between spatial and temporal variation. Moreover, this survey

method is commonly executed with the expectation that temporal variants to the field may be effectively removed during post-acquisition processing, leaving behind only spatially-varying magnetic anomalies (e.g., those of archaeological origin), despite the fact that nothing in the literature supports this assertion and much contradicts it. This may be the least costly, most convenient approach that captures the largest of anomalies, but as will be demonstrated below, such an approach may not adequately isolate true archaeological anomalies.

### 3.3 Magnetic Data Post-Acquisition Processing Techniques

Multiple post-acquisition processing methodologies are employed in the discipline. These range from virtually no processing (from small survey areas and magnetically clean datasets) to aggressive processing that removes all but the largest anomalies. These methods may or may not include subtraction of the International Geomagnetic Reference Field (IGRF) from the collected data, averaging of the data over cross-ties (if these were collected), or mathematical approximation of a gradient using the data from only one instrument (Bright, Conlin and Wall 2014; Plets, Dix and Bates 2013; Camidge et al 2010; HYPACK 2013; Tchernychev 2013). Gradient processing is accomplished by subtracting the difference of readings from a single, total field magnetometer at two subsequent times and dividing by the distance traversed. Additional methods may include high and low-pass filtering and smoothing using a moving/running average, weighted average, despiking (which removes outliers), and/or detrending (which effectively removes large-scale geological trends) (Camidge et al 2010; Bright, Conlin and Wall 2014; Breiner 1999; Henson 2006; Sheriff, Macdonald and Dick 2010).

All processing is done to accomplish a single goal: removing noise from the data in order to isolate spatial variation, allowing for effective identification of magnetic anomalies that possess the traditional archaeological dipole signature. The signature is of short duration and high amplitude when compared with geological variation and exact values are a function of multiple variables as discussed above. These may fall within a range of 5 nT to many thousands of nT in amplitude and are sensible for fractions of seconds to minutes, depending upon the size of the source of the anomaly and the speed of the survey vessel. After processing, magnetic anomalies are identified from the profile data or by visualization of magnetic data through interpolation and vector contouring in various geospatial processing programs (Bright, Conlin and Wall 2014; Breiner 1999; Henson 2006).

These standard processing approaches begin with the theoretical basis that ferromagnetic archaeological materials in the marine environment exhibit high amplitude, short duration disturbances in Earth's magnetic field that are easily contrasted with long duration

geological and solar-based contributions. This basis is true but also misleadingly incomplete. The signals of archaeological materials in the marine environment of short duration (fractions of seconds to multiple minutes) and high amplitude (5 nT to many thousand nT) do indeed contrast well with geological, crustal contributions to the field, which are of longer duration (hundreds of hours). They also contrast well with solar-based contributions that are of longer duration and lower amplitude (e.g. diurnal variation, which occurs with regular, 24-hour frequency over tens of nT). But there also exist temporally-varying, solar-based contributions that are both short duration and high amplitude; it is these signatures that are not easily contrasted and therefore not easily removed. Additionally, given the dangers of over-processing discussed above, it is highly likely that smaller, true anomalies of archaeological origin may be masked by impulsive, externally-sourced events perturbing the field, such as sub-storms. Because these sources overlap in various spatial and temporal scales, separation is nearly impossible and smaller archaeological anomalies may be eradicated through application of aggressive smoothing algorithms that attempt to remove this impulsive signature. Thus, the argument for removal of external-sources in post-acquisition processing fails to account for both of these contributions.

### 4.0 Earth's Magnetic Field and Models that Approximate It

Earth's magnetic field is comprised of multiple contributing sources; the magnitude of its total field measurement is a summation of these source magnitudes. Contributing sources can generally be categorized by their origins: internal, crustal/anomalous, and external. The principal necessity for analyzing magnetic data is to understand these contributing sources and to be able to adequately extract the portion of the total field that is noise from the portion that is signal (Regan and Rodriguez 1981). Signal for archaeologists refers to anthropogenic, spatially-varying anomalous sources of the field only; other crustal sources, internal sources, and time-varying external sources are sources of noise and must be adequately resolved out of the data in order for the archaeologist to have confidence in the assessment of magnetic anomalies of archaeological origin. Since any total field measurement is a sum total of these three sources and multiple origins, there is a strong need for knowledge of all of the components (Regan and Rodriguez 1981). The following discussion summarizes the sources and origins of Earth's magnetic field, presents an overview of the primary mathematical systems that model it, and discusses why these models are insufficient for the purposes of processing marine magnetometer data in order to isolate signal arising from archaeological anomalies.

#### 4.1 Earth's Magnetic Field

The primary contributor to the total field measurement is internal, principally from Earth's molten outer core, accounting for over 95% of the field magnitude (Maus et al 2010). The iron-rich outer core slowly moves around the inner core in patterns that evolve over time, but are predictable over shorter periods of approximately five years. This movement generates electrical current that converts to electro-magnetic energy manifested in Earth's magnetic field (Hamilton and Macmillan 2011; Regan and Rodriguez 1981).

The second contributor to the total field measurement arises principally from Earth's crust. Ferromagnetic materials on or below the ground and seafloor surface combine with geological contributors, such as fossil fuels and minerals, to add magnetic variance to the total field in these locations (Regan and Rodriguez 1981). Other sources of crustal variation are mountain ranges, ore deposits, lightning strikes, and faults (Maus et al 2010). Archaeological objects are anomalous contributors to the total field and are distinguishable from geological contributors primarily by duration. Geological sources are generally of large spatial scale (exhibit long duration perturbation signatures) whereas archaeological objects are of small spatial scale (exhibit short duration perturbation signatures); together these components contribute spatial variations measuring meters to thousands of kilometers across the Earth's surface (Maus et al 2010).

The third contributor to the total field arises from external sources, which Regan and Rodriguez have termed "undoubtedly the most dynamic, complex, and ubiquitous" contributor of the three (1981, 256). Although of many origins, all external contributors to the total field measurement are related to solar and terrestrial magnetic field interaction. The external source contributor most familiar to archaeologists is the diurnal variation in Earth's magnetic field, which is caused primarily by ionospheric and magnetospheric currents (Hamilton and Macmillan 2007). Interaction of free charges with thermospheric winds create ionospheric current vortices on the daylit side of Earth in the northern and southern hemispheres. Diurnal variation arises from the daily rotation of the Earth within this system. The magnitude of these variations are dependent on latitude, season, and solar cycle (Hamilton and Macmillan 2007; Macmillan and Reay 2012; Maus et al 2010), but are generally considered a *steady state* change. By contrast, external contributions to the total field also can cause *impulsive* changes in the field measurement, the most profound of which occurs during geomagnetic storms.

In general, geomagnetic storms occur in three phases: initial commencement, main phase, and recovery (Maus et al 2010). Fast moving solar plasma associated with coronal mass ejections produces a shock wave that collides with Earth's magnetosphere; this point in time is the commencement phase of the storm and has a dramatic, immediate effect on the

magnitude of Earth's magnetic field, also called "sudden impulse." During the remainder of the storm, the main phase, interaction between the solar transient and Earth's magnetosphere drives dynamic variations in the near-space electric current systems, such as auroral electrojets and ring current. The dynamic variations in these near-space current systems create signal oscillations at wavelengths that can mask other contributors, specifically those of crustal/anomalous origin, including archaeological anomalies. The recovery phase is a gradual reduction in externally driven field variations over a period of some tens of hours. The entire geomagnetic storm cycle lasts typically 1–2 days.

Earth's magnetic field varies in time in accordance with the sources of the variation; slow regular variation from internal sources arise over many years and rapid fluctuation from external sources can occur in seconds (Clarke, Clilverd and Macmillan 2008; Regan and Rodriguez 1981). Typical variation in Earth's magnetic field is a slow rise and fall over the course of every 24 hours due to diurnal effects. This regularity and gradual, slow oscillation of the signal lends itself to easy recognition and multiple methods, now well-established, for processing to remove it (Macmillan and Droujinina 2007). At mid-latitudes, typical diurnal variation is on the order of tens of nT every day, but hundreds of nT during geomagnetic storms. By contrast, high latitude locations exposed to auroral electric current systems in the upper atmosphere can experience field variations on the order of thousands of nT during geomagnetic storms (Maus et al 2010).

However, magnitude of total field variation alone is not a factor limiting successful removal of the external field from single instrument, total field magnetometer data for the purposes of identifying archaeological anomalies. The limiting factors are the magnitude and rate of change, and the predictability of that change. Temporal variations due to geomagnetic storms are particularly difficult to resolve. For example, sudden impulses observed in the beginning of the storm are observable in magnetic datasets across the planet. They may reach several hundreds of nT in magnitude over the course of seconds, and appear very similar in character to a classic dipole archaeological anomaly of the same amplitude. Values exceeding 1,200 nT per minute are on record in high latitude regions and exceeding 400 nT per minute in the UK, a mid-latitude region (Macmillan and Reay 2012). These appear in the profile trace as high-amplitude, short duration spikes. Figure 1 illustrates this onset signature from two days in the study dataset. The speed of onset, short duration of that onset point, and high amplitude of geomagnetic storm signatures in general make them unusually difficult if not impossible to resolve out in post-acquisition processing.

This difficulty is further confounded by a physical phenomenon of particular relevance to marine

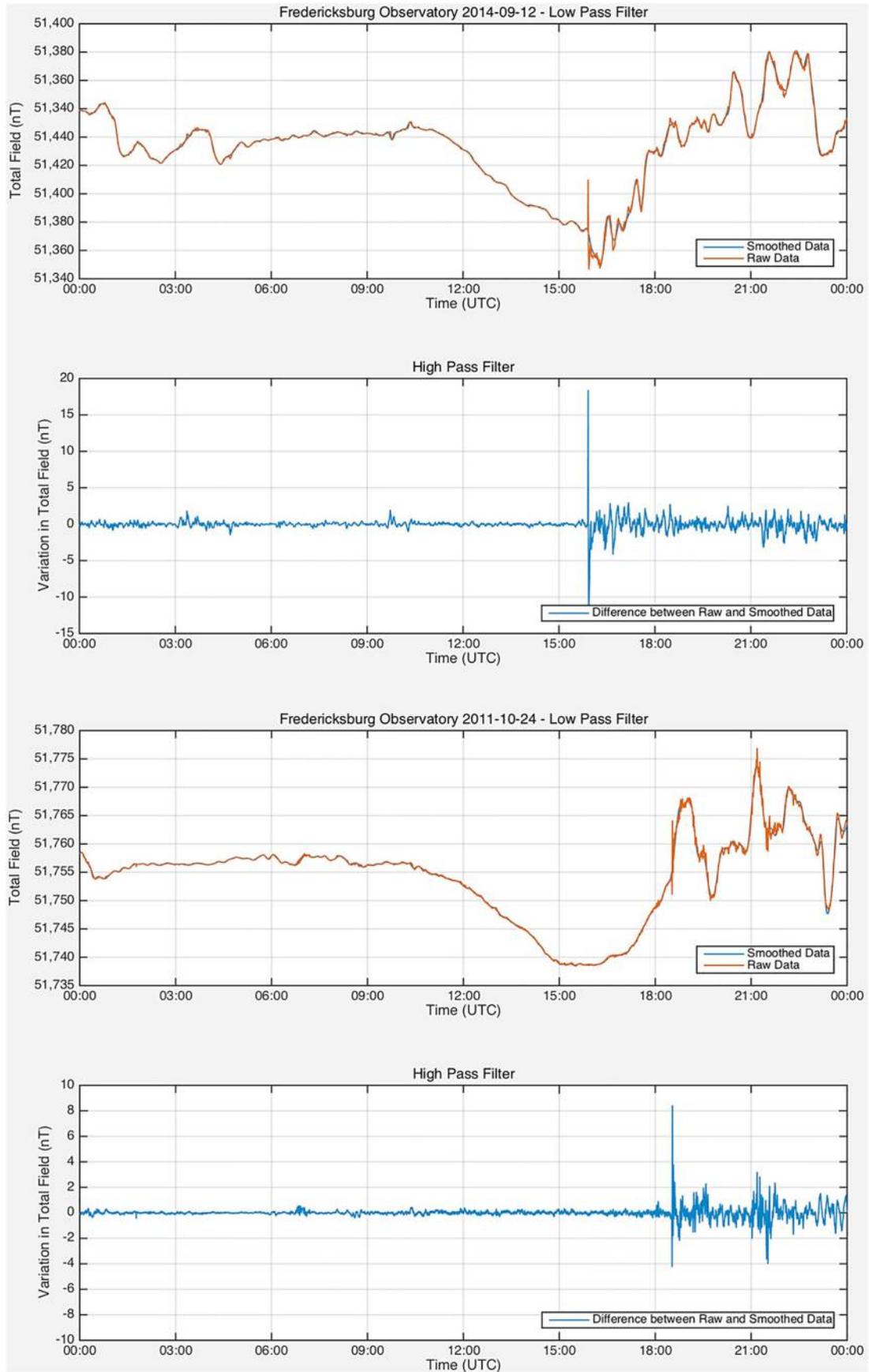


Figure 1 Geomagnetic storm onset signatures observed at Fredericksburg Observatory on September 12, 2014 (top) and October 24, 2011 (bottom).

archaeology, the ‘ocean effect.’ Electromagnetic induction arising from the movement of currents, tides, and waves is generated by the dynamo effect. This induced current moving through Earth’s magnetic field contributes to local variations that are confined to the oceans and solid Earth, and thus are only sensible in ship-towed magnetometers (Maus 2007). Seawater is highly conductive when compared either with fresh water or the crystalline rocks comprising Earth’s crust, its precise conductivity being directly related to increases in salinity, temperature, and pressure. Temperature is the most dominant variable (Maus 2007), making warm surface water on the continental shelves more conductive than seawater in the cold, deep oceans.

The additional, local variation conferred by the ocean effect may be magnified by a number of factors, specifically the presence of crustal discontinuities and geomagnetic storms. Local variation due to the ocean effect ranges from 5 nT during geomagnetically quiet times (Camidge et al 2010) to up to 100 nT during geomagnetic storms (Maus 2007) *in addition* to the external source contribution value itself. During geomagnetic storms, “a global system of current vortices is induced in the Earth, the centers of which are confined to the oceans,” (Fainberg 1980, 165). These factors are further impacted by conductivity discontinuities within the crust and mantle, specifically at the boundaries of the outer continental shelf (Olsen and Kuvshinov 2004). Therefore, the greatest potential variation to Earth’s magnetic field occurs in the oceans, in the warmer and shallower waters, near the continental shelf boundaries, and during geomagnetic storms.

#### 4.2 Understanding Magnetic Field Models

As discussed above, the primary contributor to the total field measurement is from internal sources, which also have the most stability and are predictable for an approximately five-year time period (Finlay et al 2000; Maus et al 2010). From constant observation and measurement, including analysis of more than a hundred years of magnetic field data, scientists have derived mathematical representations of Earth’s internal magnetic field and how it is changing over time. This has resulted in the publication of two global internal magnetic field models housed at the US National Geophysical Data Center (NGDC): the World Magnetic Model (WMM) and the International Geomagnetic Reference Field (IGRF). The WMM is the standard navigation model used by NATO and both the US and UK Departments of Defense. The IGRF is a reference model used internationally for research in geomagnetism (US Dept. of Commerce 2014b) and also is available within most commercial magnetic data acquisition and processing software packages.

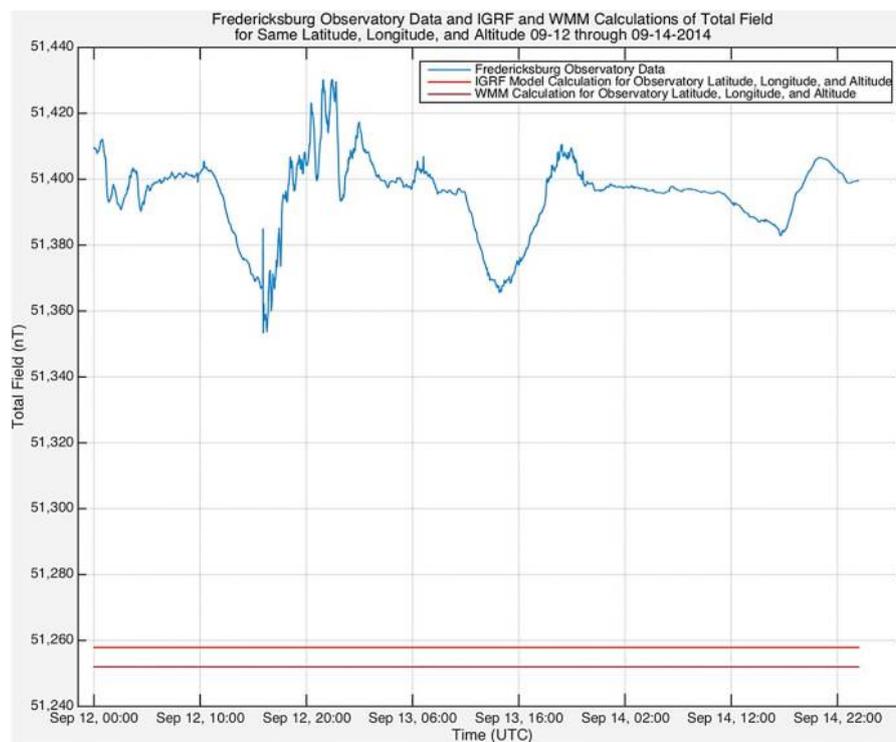
Both the IGRF and the WMM are time-varying models of the internal sources of the geomagnetic field; neither include external contributors to the total field (Macmillan and Finlay 2010; Maus et al

2010). Macmillan and Finlay (2010) discuss the limitations of the accuracy of these models in terms of two types of user error: error of commission and error of omission. An error of commission is one in which there is a difference between the internal field value and the model value. This occurs because the models degrade in accuracy over their life span; they are revised every five years for this reason. An error of omission is one in which the difference is attributable to a source of the total field that the model is *not* attempting to approximate, namely external contributions. The risk is that a user attempting to remove non-archaeological spatial and temporal anomalies from marine magnetic data using just the IGRF included in most commercial software packages will commit an error of omission; the assumption may be that the model includes all sources of Earth’s total field other than the spatial variation attributable to archaeological anomalies. Such is referred to as aliasing spatial and temporal variation.

As discussed above, any observation of the total field will include all sources and these sources span and overlap in various spatial and temporal scales; therefore, separation is nearly impossible in some cases and at the very least consideration of all sources must be made when analyzing survey data (Macmillan and Finlay 2010). Moreover, removal of the IGRF or WMM from survey data for the purposes of archaeological anomaly identification, without consideration of time-varying external contributions to the total field, will be insufficient. This is clearly illustrated by comparing the magnitude of the total field measured by a stationary magnetic observatory, with the total field value modeled by the WMM and IGRF at the exact same latitude, longitude, and time of the observatory dataset (Figure 2; US Dept. of Commerce 2014a). The variation of the observed field magnitude during this geomagnetic storm is clear.

While ongoing efforts using NASA’s Advanced Composition Explorer satellite and geospatial modeling have afforded greater predictability (Luhr and Maus 2010; Maus et al 2010; Pulkkinen et al 2007; and Pulkkinen et al 2013), impulsive variation arising from external contributions are still highly difficult to anticipate with confidence outside of an approximately 48-hour window. For this reason, it is unlikely that impulsive, geomagnetic storm contributions to Earth’s magnetic field will be included in field models in the near future. This means that quantifying impulsive external variations, necessary in the processing of single instrument, total field marine magnetic data for the purposes of identifying archaeological anomalies, must be accomplished by archaeologists using other means in order to avoid aliasing spatial with temporal anomalies (Regan and Rodriguez 1981).

Repeated observations at the same precise location are not feasible in offshore marine magnetic surveys. Tie lines may be attempted, and are beneficial for merging multiple datasets, but “the practical problems of positional accuracy and repeatability can



**Figure 2** Plot of total field observed during a geomagnetic storm occurring on September 12, 2014 with both the World Magnetic Model (WMM) and International Geomagnetic Reference Field (IGRF) as calculated for the same latitude, longitude, and altitude for that time and date (US Dept. of Commerce 2014a). Note the variation observed but not modeled; neither of the models available indicate temporal variation at the necessary detail. The models also appear to predict a field magnitude several hundred nT less than observed.

produce considerable error” (Regan and Rodriguez 1981, 288) making tie lines unsuitable for removal of temporal variation. Neither is the gradient method suitable for removing temporal variation given the short duration of the sudden storm onset signature. As discussed above, gradient processing is a mathematical model that yields rate of change over a survey area. It filters out “nearly every magnetic signal except for short duration, high intensity flux” (Bright, Conlin and Wall 2014, 13). This means that gradient processing is an exceptional processing method for geomagnetically quiet days, but will fail to remove short duration, high intensity flux, which is exactly the signature of, for example, the sudden onset of geomagnetic storms. Moreover, there are other types of impulsive, externally-sourced events perturbing the field at high latitudes, such as substorms. Thus, even gradient processing techniques will not discriminate between these two signals.

Although they may be difficult to resolve out of a survey dataset in post-acquisition processing, temporal variations due to geomagnetic storms may at least be identifiable. Data from stationary magnetometers - whether from a base station intentionally positioned near the survey area or a professionally-staffed observatory - remain the most reliable sources of information available to quantify and characterize the time-varying impulsive, external sources of Earth’s magnetic field (Macmillan and Finlay 2010). Provided the stationary magnetometer

is near enough to the survey area, the values from the stationary magnetometer can be processed and compared with the values from the survey magnetometer at the same time-stamp to confirm or refute the external contribution of anomalies identified in the survey data. Even when the stationary magnetometer is quite far away from the survey area, as will be the case for most offshore marine surveys, the signature of a geomagnetic storm sudden onset is visible across Earth’s surface. What will not be possible, however, is the removal of the impulsive signature in a manner that leaves behind obscured small nT archaeological anomalies that occupy the same frequency or magnitude.

## 5.0 Objectives and Methods

It was hypothesized that current processing methods are insufficient to remove temporal anomalies related to geomagnetic storms from single instrument, total field marine magnetometer data. Although diurnal variation appears to be removable from these data through standard processing methods (cf Ciminnale and Loddo 2001; Bright, Conlin and Wall 2014; Camidge et al 2010; Breiner 1999), variation arising from the sudden onset of geomagnetic storms is not. The immediate onset of geomagnetic storms and the fast compression of the magnetosphere creates a short-duration, high amplitude spike in the Earth’s magnetic field, evident in marine magnetometer

data, that appears similar to an archaeological anomaly and cannot be easily discerned absent simultaneous comparison with data from a nearby stationary instrument.

The objective of this study was to process, analyze, and compare single instrument, total field marine magnetometer survey and observatory datasets collected during geomagnetic storms occurring on days of Kp 5 or greater, in order to attempt to remove the geomagnetic storm signatures, thus testing the hypothesis. The use of magnetic observatory data confers an added benefit to the study: since magnetic observatories are stationary, there is no possibility of their datasets including spatial variance from geological sources or other spatially-based magnetic anomalies (e.g. archaeological resources; Macmillan 2007). Thus, any non-error variance in a magnetic observatory dataset is certainly due to a temporally-based geomagnetic contribution.

In order to test the hypothesis, it was necessary to obtain, process, and analyze raw survey and

observatory datasets that were collected during geomagnetic storms. The Database of Notifications, Knowledge, and Information (DONKI) archived at NASA's Community Coordinated Modeling Center (NASA 2014a and b) was used to identify days during the selected four-year study period of January 1, 2011 to December 31, 2014, when the geomagnetic activity index Kp exceeded 5. This level of perturbation was selected to test the hypothesis, but lower levels of Kp may also indicate a perturbed field sufficient to disrupt magnetic data quality and may obscure true archaeological sites (although the latter was not tested). The database included 37 storms. Two single instrument, total field marine magnetometer survey datasets available to the study had been collected from mid-latitude locations offshore the east coast of the US during the study period on days registering  $\geq$ Kp 5. These were collected on October 24, 2011 and June 1, 2013.

In order to supplement the magnetic survey data that were available to the study, observatory datasets

**Table 1 Geomagnetic Storms between January 1, 2011 and December 31, 2014 and Observatory Data Used for Analysis**

| Storm Dataset | Geomagnetic Storm Start Time | KP Index over Duration of Storm | Observatory Used         |
|---------------|------------------------------|---------------------------------|--------------------------|
| 1             | 2011-02-04T19:30Z            | Kp: 6                           | Isla de Pascua Mataveri  |
| 2             | 2011-03-01T18:00Z            | Kp: 6                           | Isla de Pascua Mataveri  |
| 3             | 2011-03-11T21:00Z            | Kp: 6                           | Isla de Pascua Mataveri  |
| *             | 2011-04-06T18:00Z*           | Kp: 6*                          | Isla de Pascua Mataveri* |
| 4             | 2011-05-28T06:00Z            | Kp: 6                           | Isla de Pascua Mataveri  |
|               | 2011-05-29T04:30Z            | Kp: 6                           | Isla de Pascua Mataveri  |
| 5             | 2011-06-04T21:00Z            | Kp: 6                           | Isla de Pascua Mataveri  |
| 6             | 2011-08-05T20:57Z            | Kp: 6–8                         | Fredericksburg           |
| 7             | 2011-09-09T15:00Z            | Kp: 6                           | Fredericksburg           |
| 8             | 2011-09-17T13:30Z            | Kp: 6                           | Fredericksburg           |
| 9             | 2011-09-26T16:44Z            | Kp: 6                           | Fredericksburg           |
| 10            | 2011-10-24T21:00Z            | Kp: 7                           | Fredericksburg           |
| 11            | 2012-01-24T18:00Z            | Kp: 5                           | Fredericksburg           |
| 12            | 2012-03-07T06:00Z            | Kp: 6                           | Fredericksburg           |
| 13            | 2012-03-09T03:00Z            | Kp: 6–7                         | Fredericksburg           |
| 14            | 2012-03-12T10:30Z            | Kp: 6                           | Fredericksburg           |
| 15            | 2012-03-15T15:52Z            | Kp: 6                           | Fredericksburg           |
| 16            | 2012-04-24T00:00Z            | Kp: 6                           | Fredericksburg           |
| 17            | 2012-06-16T21:00Z            | Kp: 6                           | Fredericksburg           |
| 18            | 2012-07-15T06:00Z            | Kp: 6                           | Fredericksburg           |
| 19            | 2012-09-03T12:00Z            | Kp: 6                           | Fredericksburg           |
| 20            | 2012-09-05T00:00Z            | Kp: 6                           | Fredericksburg           |
| 21            | 2012-10-01T03:00Z            | Kp: 7                           | Fredericksburg           |
| 22            | 2012-10-08T07:30Z            | Kp: 6                           | Fredericksburg           |
| 23            | 2012-11-14T01:30Z            | Kp: 6                           | Fredericksburg           |
| 24            | 2013-03-17T06:00Z            | Kp: 6                           | Fredericksburg           |
| 25            | 2013-06-01T01:00Z            | Kp: 6                           | Fredericksburg           |
| 26            | 2013-06-07T03:00Z            | Kp: 6                           | Fredericksburg           |
| 27            | 2013-06-29T03:00Z            | Kp: 6–7                         | Fredericksburg           |
| 28            | 2013-10-02T03:00Z            | Kp: 6                           | Fredericksburg           |
| 29            | 2013-12-08T00:00Z            | Kp: 6                           | Fredericksburg           |
| 30            | 2014-02-19T03:00Z            | Kp: 6                           | Fredericksburg           |
|               | 2014-02-20T03:00Z            | Kp: 6                           | Fredericksburg           |
| 31            | 2014-02-27T18:00Z            | Kp: 6                           | Fredericksburg           |
| 32            | 2014-06-08T03:00Z            | Kp: 6                           | Fredericksburg           |
| 33            | 2014-08-19T21:00Z            | Kp: 6                           | Fredericksburg           |
| 34            | 2014-09-12T15:00Z            | Kp: 6–7                         | Fredericksburg           |

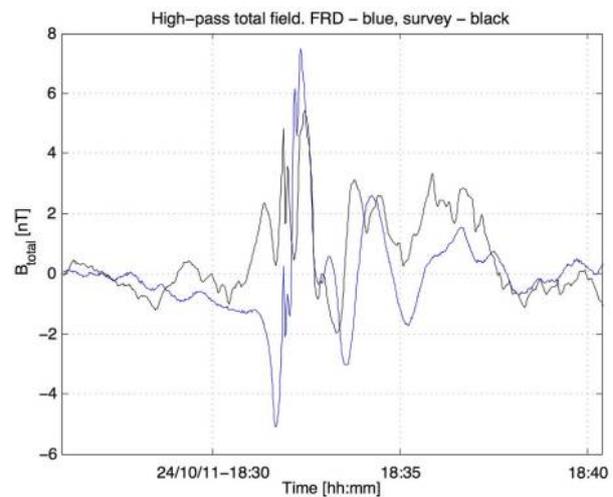
\* Data deemed invalid for purposes of study.

Storm dataset 4 (2011-05-28 and 29) and storm dataset 30 (2014-02-19 and 20) were analyzed as single storm events respectively.

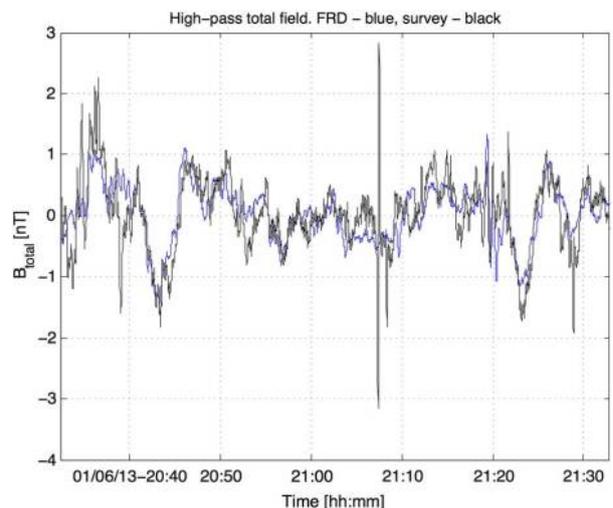
for all 37 storms also were obtained and processed (Intermagnet 2014). Observatory data for each storm were sourced only from the mid-latitude observatory that offered one-second data and was situated geographically nearest to the mid-latitude locations offshore the east coast of the US; in this case, two observatories were used (Table 1). This is relevant because, first, higher-latitude observations can be very dynamic during geomagnetic storms complicating the analysis. Second, the available survey datasets were primarily collected at mid-latitude offshore locations, yielding a more valid comparison. One-second sample rate data were used, as minute sample rate data will not reveal the short duration anomaly effects expected from both geomagnetic storm sources and archaeological anomalies. Additionally, the days before and after the geomagnetic storms were reviewed to ensure the storm's onset was captured in the analysis and a background or 'quiet time' visualization of the field was available for comparison. Because storm durations vary considerably, this yielded 71 datasets (days) for analysis, of which two days were deemed invalid for the study due to missing data (April 6–7, 2011; Table 1). The remaining 69 observatory datasets (days) were analyzed for 36 geomagnetic storms. Storm dataset 4 (2011-05-28 and 29) and storm dataset 30 (2014-02-19 and 20) were analyzed as single storm events respectively, leaving 34 storms for analysis.

All data were read and processed in MATLAB Version R2013b for consistency (Supplementary Material 1). First, observatory data were reviewed and cleaned for spikes. A 500-second moving average filter was computed and subtracted from the original signal to expose the high pass filtered component of the signal. Survey data collected on October 24, 2011 were rescaled by a factor of four and survey data originating on June 1, 2013 were rescaled by a factor of two for nearest comparison. The observatory data not associated with a survey dataset first were down-sampled by a factor of 400 and then reinterpolated using a spline function. The original and smoothed data (equivalent to a low-pass filter) were then plotted along with the difference between the original and smoothed data (equivalent to a high-pass filter). All results were plotted for comparative purposes.

While mean-centering and linear detrending are standard post-processing techniques for adjusting transect data in terrestrial total field surveys, these methods assume that the temporal variation is constant or changing linearly over the transect time period (several minutes to hours). However, a single mean value or linear trend is not adequate for these data due to the extended time period of the observatory data (24 hours). The use of a spline function over 24 hours, as described above, approximates the standard practice of subtracting a linear trend for each transect interval of several minutes to hours.



**Figure 3** Plot of high-pass filtered total field, both observed at Fredericksburg Observatory (blue) and collected during marine magnetic survey (black) during a geomagnetic storm occurring on October 24, 2011. The  $\sim 10$  nT amplitude variation caused by the sudden impulse is seen clearly in both datasets.



**Figure 4** Plot of high-pass filtered total field, both observed at Fredericksburg Observatory (blue) and collected during marine magnetic survey (black) during a geomagnetic storm occurring on June 1, 2013. The correlation between the two data sets is clear. The correlation coefficient between the depicted data is 0.71.

## 6.0 Results

Figures 3 and 4 depict plots of high-pass filtered data collected during geomagnetic storms occurring on October 24, 2011 and June 3, 2013, respectively. The plots include two data sources; the blue trace was collected at Fredericksburg Observatory; the black trace was collected during marine survey. In both survey datasets, similar disturbances were seen at the same times. This would support the hypothesis that temporal anomalies are still evident in survey data post-processing, and are most evident at the sudden

onset time. The  $\sim 10$  nT amplitude variation caused by the sudden impulse is seen clearly in both datasets collected on October 24, 2011 (Figure 3). This impulse time correlates with the arrival time of the coronal mass ejection causing the storm. Moreover, the correlation between the depicted datasets collected on June 1, 2013 is clear. The data depicted have a positive correlation coefficient of 0.71 (Figure 4).

Data collected from observatories during geomagnetic storm sudden onset also were processed and analyzed. Figure 1 depicts geomagnetic storm sudden onset occurring on September 12, 2014 and October 24, 2011. This impulsive signature of  $\sim 35$  nT and  $\sim 15$  nT, respectively, over the course of seconds is clearly evident and corresponds with the arrival time of the coronal mass ejections causing the storms. In both cases, prior to the arrival time, there is little perturbation of the field as evidenced by the low amplitude ( $< 1$  nT) of the high pass filtered data. After the arrival time, there is increased perturbation of the field as evidenced by the higher amplitude ( $\sim 1\text{--}10$  nT) of the high pass filtered data. This increased perturbation is associated with the main phase of the storm. The same signature is observed in all 34 storms analyzed (Supplementary Material 2). This also supports the hypothesis that temporal anomalies remain evident in the data post-processing. Given that this storm noise is the background from which spatially-varying signals must be identified, its presence renders the data useless for identification of archaeological resources on the order of tens of nT in amplitude.

The observatory data were subjected to additional analysis in order to assess the likelihood of geomagnetic storm sudden onset signatures being misinterpreted as archaeological resources. For this analysis, the processed observatory data for days of Kp 5 or greater were qualitatively categorized as either containing or not containing storm sudden onset signatures that may be misinterpreted as the magnetic signature of archaeological resources. The categorization was based on the magnitude and duration of the change of the high pass filtered data as well as field experience of the authors. Because the outcome of the classification is one of only two possibilities, and the storms are statistically independent, a Binomial distribution was used. The Clopper-Pearson method of estimating the confidence interval was selected based on a comparison of methods by Newcombe (1998).

Of the 34 storms analyzed, 100 percent possessed storm onset signatures that were considered to be potentially misleading, resulting in aliasing temporal variation (the storm sudden onset signature) for spatial variation (archaeological anomalies of interest). Based on this qualitative analysis and using the Clopper-Pearson method of estimating a Binomial confidence interval with a 95% confidence level, it is estimated that 89.7 to 100 percent of geomagnetic storms occurring on days of Kp 5 or greater will generate

magnetic anomalies that may be misinterpreted as archaeological sites. These results apply exclusively to surveys conducted at mid-latitudes and sudden impulses generated by coronal mass ejections. These results do not apply to surveys conducted at high latitudes and signatures arising from other types of impulsive geomagnetic phenomena, such as substorms.

## 7.0 Conclusions and Recommendations

Post-acquisition processing of these data was unable to remove evidence of a known geomagnetic storm sudden onset (see Figures 1, 3, and 4 and Supplementary Material 2). And while this exercise was illustrative, it was based on precise knowledge of the geomagnetic storm sudden onset time. A marine archaeologist analyzing a real survey dataset without knowledge of the geomagnetic storm occurrence and sudden onset time may have concluded that the storm's signature was an archaeological anomaly, regardless either of aggressive smoothing and filtering or of application of otherwise highly effective techniques, such as gradient processing.

Moreover, aggressive processing is not advisable. The filtering methods discussed herein attempt to separate contributions by time varying component, and in any single dataset the scales of temporal variation of the multiple contributors to the field will overlap, making this impossible (Camidge et al 2010). Breiner (1999) advises never to remove or filter out anomalies whose wavelength is on the order of the sources of interest and this is certainly the case with certain signal components associated with geomagnetic storms. Similarly, Kvamme cautions that though data processing is an essential and beneficial activity, "it can also be dangerous. Insufficient processing can leave important features unseen while improper methods might actually remove significant features from the data. [Contrastingly], data can be over-processed such that spurious features are introduced" (2006a, 236). Filtered signals are shifted in amplitude and time, the process of which introduces errors ranging from minimal and inconsequential to major and disastrous. Successful processing, such as it has been developed and in use by the discipline, is therefore inherently dependent upon fidelity in data acquisition, high data density, and lack of geomagnetic perturbation.

These findings suggest a number of recommendations for improving marine archaeological resource identification practices. First, avoid conducting magnetic survey during a geomagnetic storm, regardless of instrumentation used. Rapid, strong temporal fluctuations of Earth's magnetic field relating to the sudden onset of a geomagnetic storm can be easily mistaken for archaeological anomalies and the subsequent main phase of the storm can mask them. Breiner (1999) recommends against collecting data with the objective of removing in post-acquisition processing

the temporal variations arising from a geomagnetic storm. Additionally, Henson explained that variations arising from unpredictable, abnormal solar activity “are unacceptable for effective remote sensing” (2006, 22). The results of this study support both observations. Surveyors may obtain the geomagnetic forecast at [swpc.noaa.gov](http://swpc.noaa.gov), but are advised to consult a space weather forecaster who can advise the survey team on geomagnetic activity, effectively preventing costly rework.

It is worth noting that error in the prediction of geomagnetic storm onset time averages ~10 hours. The severity of the storm, however, is far more difficult to predict and depends on the orientation of the interplanetary magnetic field observable by satellite-based solar wind monitors positioned at Lagrangian Point L1. This position - close to earth - means that space weather forecasters can gauge the severity of a storm only about 40 minutes before the onset of the geomagnetic disturbance. In the datasets analyzed herein, forecasts appeared often to be highly accurate regarding storm arrival time, though some storms arrived earlier and some later than the predicted times. Therefore, it would be inappropriate to assume that survey can be safely conducted up to the time of the forecasted storm onset or to assume a lower level of severity. Rather, when a storm is pending, the most appropriate approach is to await the end of the recovery phase when the observed total field variations return to background levels.

Secondly, use a base station or gradiometer. It is universally agreed that these configurations will be more effective than a more distant observatory when attempting to identify and remove temporal variance and isolate spatial variance in marine magnetic data.

Thirdly, if no base station or gradiometer is available, and *especially* if survey must be conducted during a forecasted geomagnetic storm, before processing and selecting anomalies, obtain one-second observatory data from the nearest observatory in a geomagnetic latitude similar to the survey area. Process both datasets using the same methods, and plot both processed datasets together to obtain a comparative basis for selecting magnetic anomalies. While this approach may allow clear distinction of the sudden onset of the storm from an archaeological anomaly, the high variation in the background field still may mask small archaeological anomalies. Therefore, this approach is recommended with extreme caution as the quality of any marine magnetic dataset collected during high Kp times will be suspect; small archaeological anomalies will likely be lost behind the signature of the storm, which can last 1–2 days.

Finally, utilize site delineation practices as part of primary identification efforts. Although precise repeat measurements at the same location using the same heading is not feasible in marine environments, traversing additional survey lines of increasingly fine spacing around possible anomalies should be a regular part of

archaeological resources identification practices. Initial passes of a survey area should not exceed 30-m line spacing; greater spacing risks missing archaeological resource anomalies altogether (Bright, Conlin and Wall 2014; Cambridge et al 2010). Then, make subsequent passes at half the survey distance around suspected anomalies for better refinement and confirmation of the anomaly signature and location. This approach is regularly utilized in terrestrial archaeological identification practices (Breiner 1999 and Bevan 2006) and was recommended as early as 1972 for marine magnetometry (Clausen and Arnold; cf Cambridge et al 2010). The benefit of this approach is that multiple passes can confirm a short duration, high amplitude anomaly in the data as a spatial variant to the field (i.e., archaeological in origin); if the anomaly signature is missing on subsequent passes, then it can be confirmed as a temporal variant.

As discussed above, magnetic data processing methodologies vary greatly; it is further acknowledged that data analysis and interpretation is a highly subjective activity. This study was not designed to resolve either the methodological variation or the subjective nature of marine magnetic data analysis. Instead, the hope is to bring more consistency and fidelity to raw datasets at the outset, prior to processing. Collecting data with other instrument configurations and with consideration of the forecasted onset of geomagnetic storm conditions, as well as using appropriate processing techniques, will ensure spatial variation is not aliased with temporal variation. The proposed methods may better characterize true archaeological anomalies, allowing for improved accuracy in analytical interpretation and thus improved management of archaeological resources located on the submerged US outer continental shelf.

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