GEOMAGNETIC ACTIVITY FORECAST – A SERVICE FOR PROSPECTORS AND SURVEYORS

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ABSTRACT

We propose to develop a computer based geomagnetic activity forecast service with the objective to provide on a daily basis the level of expected geomagnetic disturbance at middle, high, and polar cap magnetic latitudes up to two days ahead. The scheme will be based on real time solar wind, magnetospheric and ground-based geomagnetic data and archived solar and geomagnetic activity reports. Prospective users of the service include firms which consult oil companies on prospecting and well drilling and enterprises which perform magnetic anomaly surveys. Both rely on *in situ* magnetic field measurements which are practically unusable if taken during times of intense temporal geomagnetic field variations. They are therefore interested in a forecast of the geomagnetic activity in order to optimize their operations planning.

1. INTRODUCTION

The geomagnetic field undergoes temporal variations on a wide range of time scales. Variations of less than a month period are solely externally driven, i.e., they reflect changing conditions of the sun and the solar wind (including the embedded interplanetary magnetic field – IMF). They contain recurring as well as transient components. Bursty solar events such as coronal mass ejections (CME) and solar flares (sf) are not predictable with our current understanding of the sun and solar dynamics. However, near-term predictions of the level of geomagnetic activity (predictions over a time span of about 2–3 days ahead) can already be made with reasonable probability.

Predictions of the level of geomagnetic activity which is expected to be encountered over the next two days on or near the earth's surface in specific geographic regions are highly desired by various users whose field operations are often guided by reference to the geomagnetic field. They include

- Prospecting companies, specifically oil companies, which perform directional drilling controlled by devices based on the local magnetic field vector orientation.
- Magnetic anomaly survey enterprises which map magnetostatic anomalies originating in the Earth's crust and mantle.

Both user groups conduct magnetic field measurements which are often complicated, time consuming and consequently expensive. However, their applicability decreases substantially with an increasing level of disturbance of the geomagnetic background. The users have thus a viable interest in gaining access to reliable short-term predictions of the level of geomagnetic activity. It puts them into a position in which they can take informed decisions in their operations planning over the next few days. Taking the right decision will undoubtedly save money in their field operations. We therefore intend to provide a quantitative, latitude and time dependent, forecast of geomagnetic activity over a two-days time span.

We propose to develop a computer based system for targeted geomagnetic activity forecast. Our service will comprise a description of current and expected geomagnetic activity together with a graphical scheme displaying the level of disturbance of the geomagnetic field expected over the next three hours, the rest of the present day, one day ahead, and two days ahead. The geomagnetic disturbance level will distinguish between different geographic areas – middle, high and polar cap latitudes – and will be scaled according to user requirements. Daily updated forecasts will be presented on a dedicated Web site.

The forecast will be based on real time solar, heliospheric, solar wind and IMF data acquired by the SOHO and ACE spacecraft, combined with real time GOES data and near real time magnetic field variation data obtained from geomagnetic observatories and variometer stations in Greenland and Scandinavia. Other data sources include publicly available solar activity reports and our own archives of solar and geomagnetic activity recorded during the most recent solar rotations.

Our effort builds on the collaboration between three primary parties. The Danish Meteorological Institute (DMI) assumes the role of a service provider. The internationally operating firm Baker Hughes INTEQ represents industrial users and is particularly active in oil industry consulting. The Geological Survey of Denmark and Greenland (GEUS) is a government affiliated user who contracts with the end users of geomagnetic activity forecasts, namely private companies which conduct airborne geomagnetic surveys.

2. STATUS OF DMI'S FORECAST SERVICE

We have recently begun to devise a scheme to generate semi-quantitative geomagnetic field disturbance predictions based on a variety of publicly accessible data as well as data from DMI's own sources.

Our preliminary prediction is generated every morning shortly before 09 UT and appears on a web page which is at present only available to authorized DMI staff. Fig. 1 gives as an example the web page generated in the morning of Oct 28, 2002.

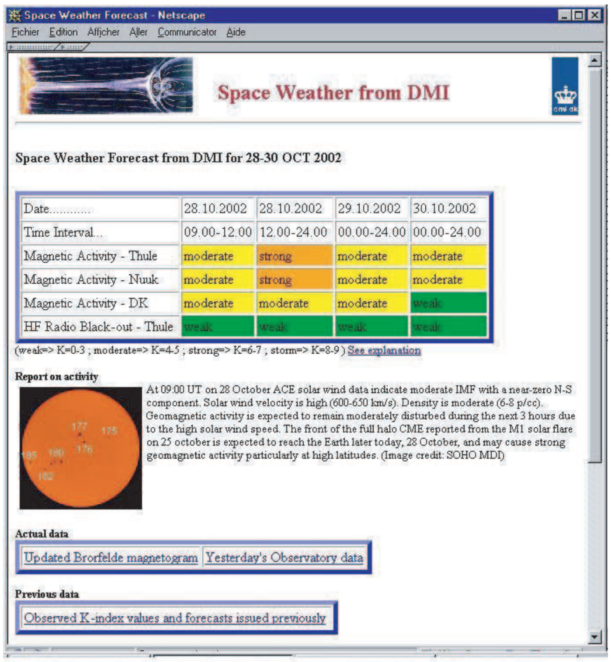

Figure 1. Preliminary setup for DMIs Geomagnetic Activity Forecast web page (for internal use only). This page is manually updated every workday shortly before 09 UT.

All observed and forecast geomagnetic activity data are converted into a latitude dependent geomagnetic disturbance class. We distinguish four disturbance categories at each observation station, namely "weak", "moderate", "strong" and "severe storm", and we use different activity thresholds which are related to the local K index (see Fig. 2). The K index is a function of geomagnetic latitude, designed such that all latitudes exhibit comparably large K numbers during a global magnetic field disturbance. Fig. 3 shows the magnetic field observations from the same day (which, of course, were available to us only after midnight of that day, i.e. in the early morning hours of Oct 29, 2002).

Our prediction method is at present almost entirely manually driven. We examine data from various sources including SOHO observations of the sun and solar corona, ACE real time solar wind and IMF data, and ground-based magnetometer measurements. We further access reports on past solar and geomagnetic activity, including those issued

activity	K value	BFE range (nT)	NAQ range (nT)	GDH range (nT)	THL range (nT)
weak	0 - 3	≤ 48	≤ 192	≤ 144	≤ 144
moderate	4 - 5	49 – 144	193 – 576	145 – 432	145 – 432
strong	6 - 7	145 – 396	577 – 1584	433 - 1188	433 - 1188
storm	8 - 9	> 396	> 1584	> 1188	> 1188

Figure 2. Selected geomagnetic activity classes at Danish and Greenlandic observatories used in our forecast scheme.

by the Space Environment Center (SEC) of the US National Oceanographic and Atmospheric Administration (NOAA). We subsequently evaluate these data with respect to their potential geoeffectiveness. Geoeffectiveness in this context refers to solar events which have a detectable impact on geospace which is the part of space physically connected to the planet Earth. Geospace includes the magnetosphere and its boundary layers, the ionosphere and atmosphere but excludes the heliosphere and the interplanetary space.

Transient solar events such as solar flares (sf) and coronal mass ejections (CME) – which can sometimes be very violent – and longer lasting phenomena such as high speed streams emerging from coronal holes are not always geoeffective. The source regions need to be suitably positioned with respect to the earth in order to have an impact on geospace. We consider therefore the location from where coronal hole streams or CME have been reported to originate, and the speed with which they are reported to propagate when we assess their influence on the state of the magnetosphere. Very often different velocity estimates are published, and the exact time of arrival at the magnetopause is poorly determined. The travel time from the sun to the earth is usually between 1 and 4 days (i.e. the velocities range from 1800 km/s down to 400 km/s). We have therefore until now restricted our prediction of the level of geomagnetic activity resulting from the most recent bursty solar events to the announcement of the day of their expected arrival and the expected intensity class of geomagnetic disturbances. A comparable uncertainty exists for the time when we expect to experience the effect from a coronal hole when it is observed to rotate into a geoeffective position.

When the development of a solar event has been followed for a certain time by observers the uncertainty is gradually reduced and the prediction of the time of arrival becomes more accurate. That means in practice that predictions for today bear a higher degree of certainty than those for tomorrow, and these again bear a higher grade of certainty than those for the day after.

This situation changes dramatically when the ejecta from a CME or a high speed stream pass the ACE spacecraft residing at the Lagrangian libration point (or any other spacecraft positioned in the solar wind

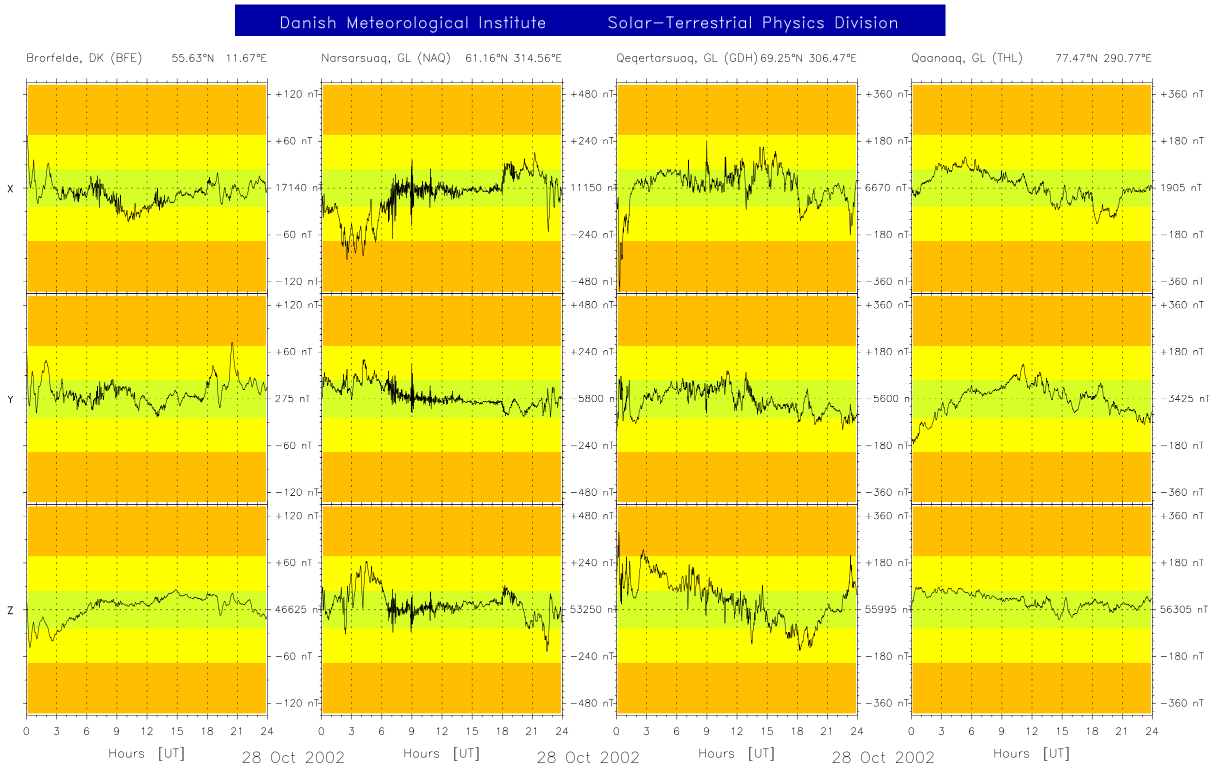

Figure 3. Variation of the magnetic field components in geographic northward (X), eastward (Y) and downward (Z) directions recorded on Oct 28, 2002, at the Danish and Greenlandic observatories.

in front of the Earth's magnetosphere). When ACE records the shock front associated with the ejecta we can expect to notice the start of geomagnetic disturbances within the next 1–2 hours. Similar considerations apply to coronal hole streams. Once recorded at the Lagrange point the stream will take one hour at maximum to start buffeting the magnetosphere. We therefore divide the prediction for the present day into two intervals, the next three hours (09–12 UT) and the rest of the day.

3. METHODOLOGY

We will devise a scheme which shall be based on a well defined mathematical algorithm. It will be divided into two branches which work with different data sources and are therefore treated differently.

3.1. Hour–ahead Forecast

Neural network based models for prediction of the auroral electrojet index AE and the ring current index Dst for one hour ahead are now in operational use [Gleisner and Lundstedt, 2001; Lundstedt *et al.*, 2002]. The predictions can be improved by incorporating observed ground-based geomagnetic field variations. In the absence of major solar wind transients, a one hour ahead forecast can be extrapolated a few hours into the future, as shown by models predicting the geomagnetic storm index Dst several hours ahead from solar wind data alone [Wu and Lundstedt, 1997]. The likelihood that solar wind transients will occur during the next 3 hours or so must, however, be determined by the methods described in the next subsection.

We propose to use neural networks to forecast the geomagnetic activity with a lead time of up to three hours. Neural networks can be viewed as a general nonlinear filtering technique. They can be adapted to accommodate a diverse set of input data, and be optimized to handle both continuous and discrete input and output variables. The input data on which the forecast will be based include

- real time solar wind data
- real time geomagnetic activity parameters

3.2. Day–ahead Forecast

For many purposes a forecast for a few hours ahead is not sufficient. User requirements force us to go beyond a lead time of 1–3 hours, which means that we can no longer rely on solar wind data as the sole input to the forecast scheme. Different techniques have to be applied which require additional input parameters.

The solar wind conditions are determined by the state and activity of the Sun. From there, it takes the solar wind plasma around 2–4 days to reach the Earth's magnetosphere. Remote observations of the

Sun – by SOHO, for instance – should in principle allow us to first produce forecasts of the near Earth solar wind conditions with a 2–4 days lead time (depending on solar wind speed), and then use the latter to produce ground geomagnetic forecasts for the following few hours as described above. Unfortunately, our lack of detailed understanding of the relations between conditions on the Sun and in the solar wind, and the primitiveness of available physical models, largely prevents us from following this simplistic scheme.

Therefore we have to recede to more indirect methods. A survey of presently used techniques reveals that day–ahead geomagnetic forecasts normally rely on a combination of two methods: (a) statistical methods which build on persistence and ≈27-day periodicities, and (b) the subjective opinion of an experienced forecaster who bases a decision on the occurrence of certain events on the Sun, most notably CME but also sf, coronal hole passages, and disappearing filaments. The methods employed have changed little over the last decade despite the fact that we have much better coverage of real time or near real time solar observations.

The method we propose combines old with novel techniques. We start with the observation that under some circumstances, geomagnetic activity is actually dominated by persistence and periodicities. Under those circumstances, we can describe the geomagnetic variations fairly accurately using relatively simple filtering techniques. The filter includes a time-varying response to the observed solar wind, to the predicted solar wind, and to an estimate of the strength and direction of the interplanetary magnetic field, and incorporates auto regression of the geomagnetic activity parameter itself. The filter should be able to take into account some forms of nonlinearity. We propose to use neural networks for this purpose and base the forecast on

- real time solar wind data
- real time geomagnetic activity parameters
- predictions of solar wind speed and interplanetary magnetic field directions from empirical solar wind models, e.g., the Wang-Sheeley model
- estimates of interplanetary magnetic field directions from solar magnetograms

We expect that this approach will allow a fairly accurate forecast during periods when the solar wind is dominated by regular, large-scale variations of the quiet Sun. Longer periods of this kind are relatively frequent in the declining and minimum phases of the solar cycle and occur intermittently during the maximum phase.

The main problem is to know one to three days ahead if the circumstances will be such that we can employ these statistical methods (and if so, which method is preferable) or if the conditions for their applicability break down. We propose to devise a scheme for automatic validation of such conditions and for selection of forecast methods and parameters through classification of solar transient events. Specifically, we will use cluster analysis and neural network classifiers to evaluate the effects of transient events on the Sun and in the solar wind. The transient events to be monitored include

- coronal mass ejections (CME)
- solar radio bursts
- solar flares (sf)
- solar X-ray enhancements
- solar energetic particle (SEP) enhancements

Some of these parameters allow us not only to issue a warning against using the forecast methods described above but also to give a limited amount of information on upcoming disturbances. This information includes the timing, type, and approximate magnitude of disturbances.

3.3. Primary Data Sources

The primary data sets to be used are being acquired with existing equipment so that no new monitoring systems and sensors need to be deployed. The data can be organized into four categories:

- remote sensing of the Sun and solar corona (using MDI, EIT and LASCO on SOHO and ground-based solar observatories)
- *in situ* sensing of the solar wind and interplanetary magnetic field (using SEPAM, MAG, EPAM and SIS on ACE)
- *in situ* sensing of solar X-ray and energetic proton flux in the magnetosphere (using sensors on GOES)
- *in situ* sensing of the magnetic variations at ground level (using distributed magnetometer stations)

All data of relevance to and required for conducting this project can either be collected from publicly accessible WWW and FTP servers or originate from facilities operated by DMI.

4. USERS AND USER NEEDS

4.1. Airborne Geophysical Survey

Airborne geophysical surveys which exploit measurements of the magnetostatic field generated by the magnetisation of the Earth's crust are used as an aid in the general understanding of the geology and specifically in the search for minerals. Measurements are carried out from small aircraft or helicopter along parallel lines with separations of about 200–500 m with a sampling rate of about 10 m along the lines. In Greenland, altitudes of 120–300 m above the terrain have been used. The data are usually presented as maps (Fig. 4) or along profiles. The total amount of flight line kilometres in the map shown is 90,000 km and the total cost for acquiring this amount of data is approximately 500,000 Euro.

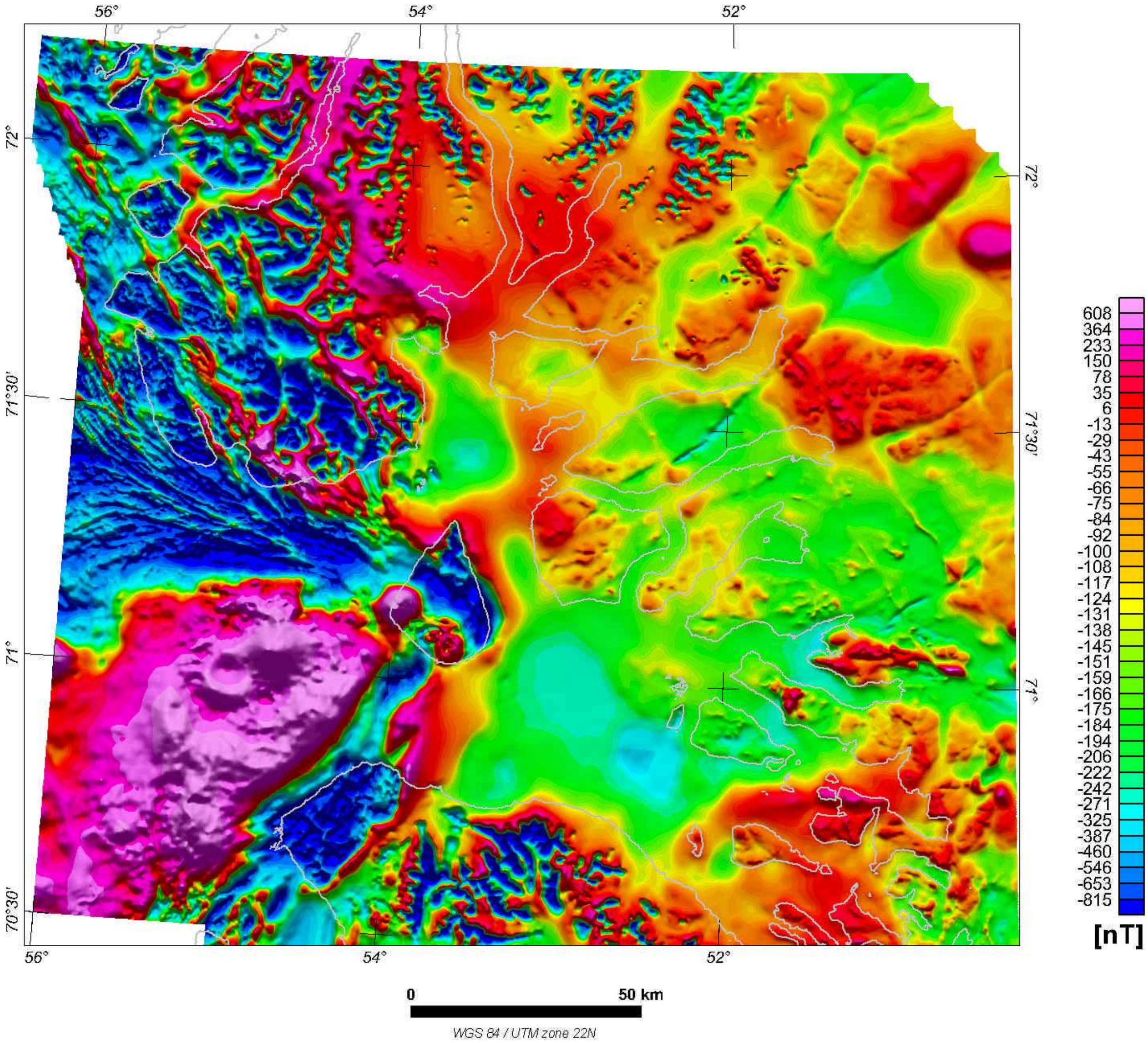

Figure 4. Magnetic field intensity of the crust after subtraction of the field originating from the core of the Earth. The area is from the west coast of Greenland around Uummannaq. The coast line and border of the Greenland Ice Cap are shown by grey lines.

Temporal variations of the magnetic field (which are caused by electromagnetic processes in the ionosphere) must be removed from the measurements. This is done by using magnetic reference measurements at a fixed station within the survey area. However, in order to achieve sufficiently accurate correction the magnetic field deviation caused by ionospheric activity must be weak. Airborne measurements are very expensive, and it is of great value to obtain a prediction of the magnetic variations, such that flights are avoided during periods when the geomagnetic activity exceeds a specified threshold. The duration of each flight is about 6–8 hours, which corresponds to 1000 km line data. Thus, an early morning prediction covering the rest of the day is required.

The geomagnetic activity forecast will be integrated into an ongoing program on Airborne Geophysical Surveys in Greenland which is managed by GEUS and carried out by commercial companies. The activity has two main objectives, stimulating mining exploration activity in Greenland and providing modern geophysical data of high quality that will improve our understanding of the geology of Greenland (which is also a prerequisite for successful mining exploration).

4.2. Directional Well Drilling

Directional well drilling for oil and gas exploration relies heavily on magnetic field guidance. The largest single error source when drilling with a conventional tool is the inability to accurately define the direction of drilling as a result of the uncertainty about the Earth's magnetic field orientation. Knowledge about the spatial (static) and temporal variation of the geomagnetic field is necessary for reducing this error. Information about the spatial variation is obtained from aeromagnetic anomaly data acquired during magnetically quiet times. By applying advanced mathematical techniques a skilled survey management team can use this information to achieve a considerably improved directional drilling accuracy.

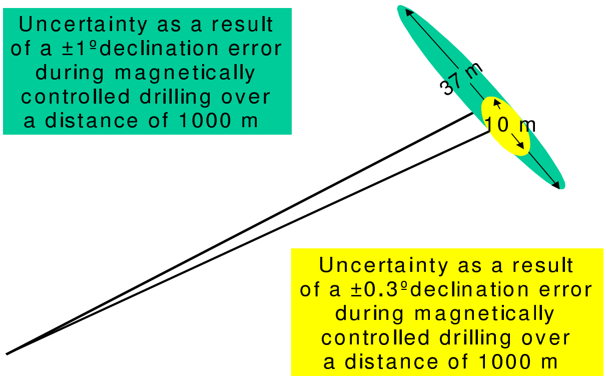

Figure 5. Effect of declination uncertainty reduction on directional drilling accuracy.

Time series of the temporal variation can be obtained from a fixed reference magnetometer station. Since a reference magnetometer is almost always located at a considerable distance from the well its recordings cannot be used for an accurate quantitative correction under magnetically disturbed conditions. During disturbed periods the declination at a midlatude site, e.g., at a well in the North Sea, can easily deviate by 0.5°from its quiet time value, and during major magnetic storms it can be as much as 1.5°. In the present situation the survey management team can choose between using and discarding magnetic measurements which have already been conducted in the well being drilled. Instead of having only *a posterori* information it would aid survey management considerably for planning and controlling directional drilling if *a priori* information about geomagnetic activity were available.

5. SERVICE PRODUCT EVALUATION

It must be understood that the goal of the project is not to predict exactly time and magnitude of the disturbance. The goal is to offer the user a tool which enables him to evaluate whether or not useful magnetic measurements could be performed today or tomorrow, or if they should rather be postponed.

The evaluation process proceeds along two lines. One focusses on a statistical analysis of the predicted *versus* the observed geomagnetic activity levels, specifically on the distribution of errors, their dependence on activity, season, geomagnetic latitude and other parameters. The prediction error analysis is coupled to the algorithm development insofar as observed trends in the error distribution initate adjustment of the algorithm and the prediction scheme.

The other line addresses the performance of the algorithm and is based on the user's assessment of the usefulness of the forecast product. It thus constitutes a significant project contribution from the user's side. The prime evaluation criteria can be stated as follows

- How often would the user have decided to postpone a planned operation as a result of receiving a forecast for unfavorable geomagnetic conditions?
- How often would the decision have been right, how often wrong?
- How much time and money could have been saved or lost over a year if the user would have relied entirely on the forecast, in contrast to a situation in which he would have totally ignored the forecast?

The project work flow is outlined schematically in Fig. 6.

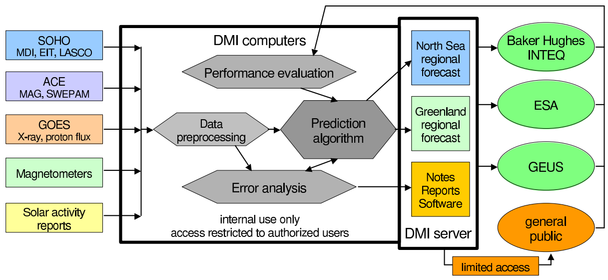

Figure 6. Geomagnetic Activity Forecast: work flow diagram.

6. THE NEED FOR A EUROPEAN SPACE WEATHER PREDICTION CAPABILITY

The quality and reliability of a space weather forecast is a function of the time span for which the forecast is issued. The forecast is more certain the smaller a time span is considered. The next 12 hours are of highest relevance to the users which we address with this service. This is an important argument for an operational European space weather program. Until now the most comprehensive space weather reports and predictions are made in the United States, and these are usually issued during day time and up into the evening hours in the US. They are thus already about half a day old when examined by Europeans. A space weather service which generates a forecast during European early morning hours and publishes predictions for the next 12 hours (for which predictions are most reliable) has great advantages for European users.

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