SPACE WEATHER INTRODUCTORY COURSE

SWIC

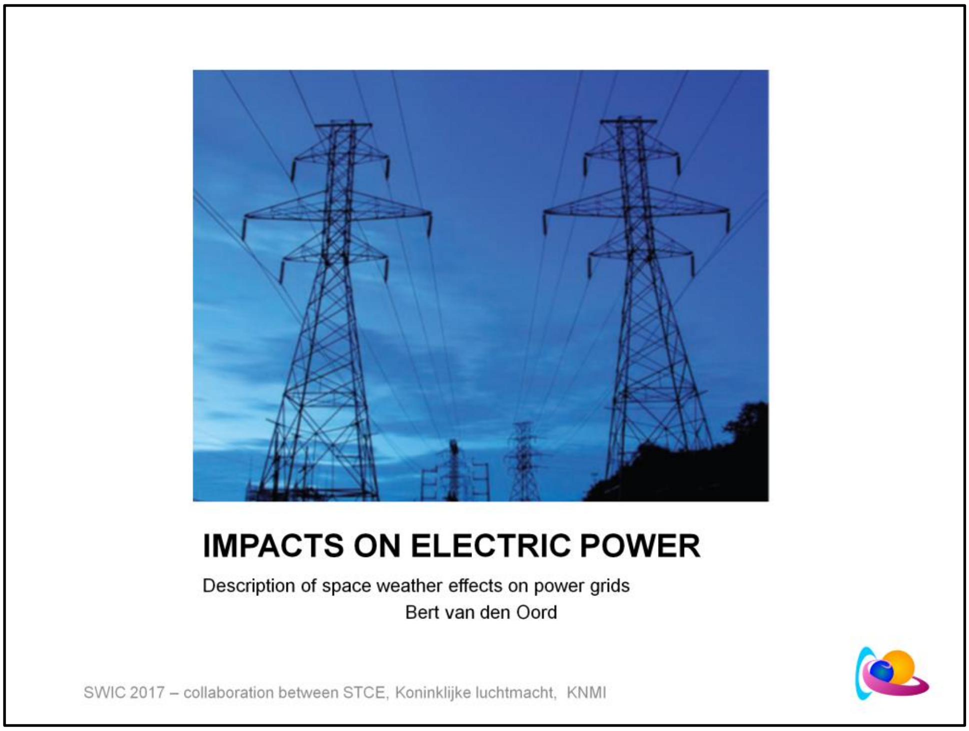
Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

May 2017



Literature

Space Weather Risk, Pirjola et al., doi:10.1029/2004SW000112

Continental Scale Modelling of geomagnetically induced currents, Viljanen et al.,DOI: 10.1051/swsc/2012017

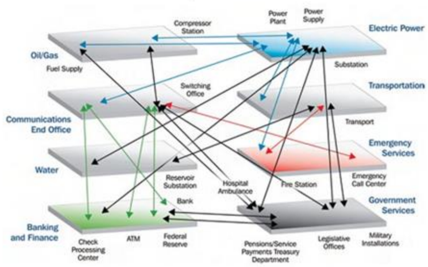
Why Space Weather is Relevant to Electric Power Systems, Gaunt, DOI: 10.1002/2015SW001306

LLOYD'S 2013: Solar storm risk to the north American electric grid

VITAL SECTORS

For societies both electric power and communication are essential to avoid

- Casualties
- Economic loss
- Societal disruption



Insurance:

- US 2000-2010 power grid related payments: 119-188 M$/yr (10% space weather)
- Most extreme case 1 trillion $ i.c.o. Carrington event (GNP 2015 18 trillion $)

Inductive currents can cause fire in transformers if the network is not properly configured.

The fact that transformers on a hemisphere may be damaged constitutes the greatest risk from space weather:

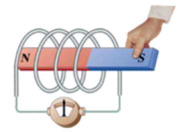
There are few spares and the lead time is long

Electric power is needed to make society work. There have been a number of black outs but these also occur due to other courses. The only big danger is that a Carrington event would cause failures on a complete hemisphere and that many transformers would be destroyed. There are too fewspares and black outs could last for weeks resultng in a collapse of society. Regional blackout are inconvenient but constitute no threats

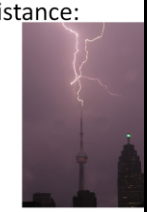
HISTORIC BLACKOUTS

The damage during the 1989 Quebec Blackout 13,2 Canadian Dollars

PHYSICAL ORIGINS OF DISTURBANCES

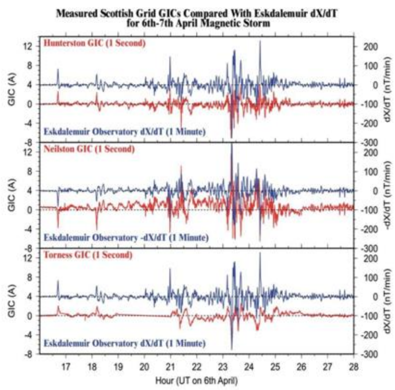


- Coronal mass ejections cause changes in the magnetic field of the Earth.
- Changing magnetic fields induce electric fields (Faraday's Law) in the ionosphere and at the Earth's surface that try to oppose the magnetic changes
  - Largest horizontal voltages measured 45-55 V/km in Norway March 1940
  - Normally 0.1 V/km; during storm conditions 5-10 V/km
- These electric fields drive geomagnetically induced currents (GICs)
- The currents run at locations with highest conductivity/ lowest resistance: oceans, power grids, pipelines, cables, railway networks
  - Low conductivity increases induced electric fields
  - Exception are costal areas that are more vulnerable despite high conductivity.



See https://www.lloyds.com/news-and-insight/risk-insight/library/natural-environment/solar-storm
See Pirola et al., Space Weather Risk 2005 Space Weather Vol 3 S02A02
Coastal regions experience an enhancement in the surface electric field due to the high conductivity of seawater. This can be thought of as the seawater carrying extra charge, and the nearby, grounded, transformers provide a path for the current to flow. The enhancement from the coast effect increases exponentially towards the coast
See also Lloyds report

EXAMPLE GIC MEASUREMENT AND EFFECTS IN POWER STATIONS



The rate of change of the north component of the magnetic field (blue trace) recorded at Eskdalemuir observatory in the Scottish borders and the simultaneous GICs (red trace) measurements at three Scottish power stations during the magnetic storm of 6th April 2000. Image: BGS (NERC)

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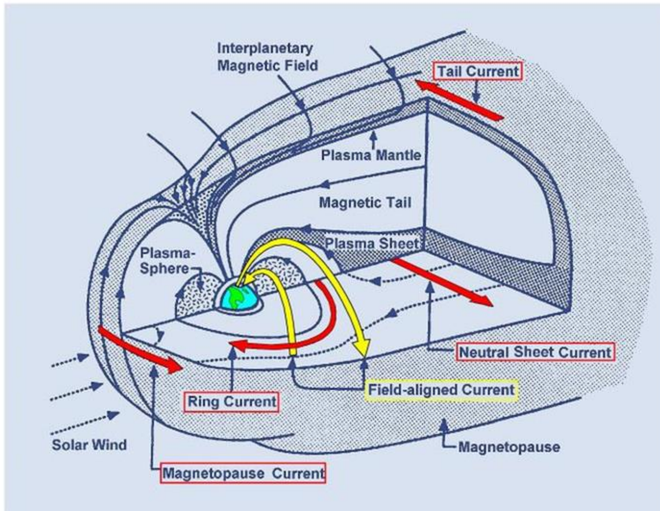
This shows that the there is a strong correlation between the GIC and the excusions measured in power stations

CHANGES IN EARTH MAGNETIC FIELD BY CME



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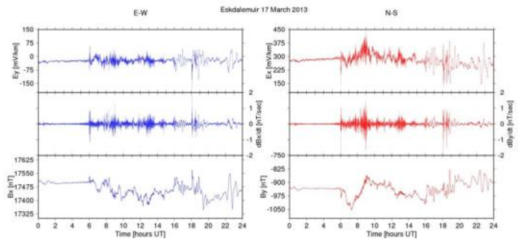
The artist impression (Movie) shows that the Earth Magnetic field is strongly perturbed by the CME. The real topology is however more complex

TOWARDS EFFECT CALCULATION IN A GRID

Two steps required:

1. Determine the geoelectric field associated with the geomagnetic variations.

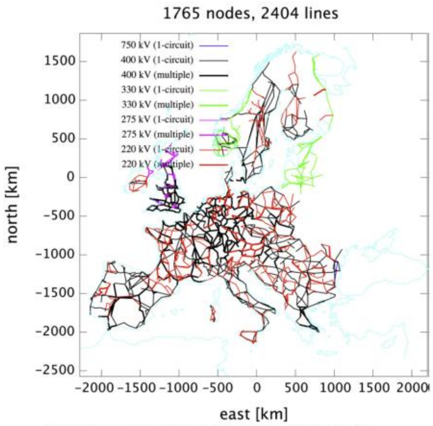


2. Determine the geomagnetically induced currents in a conductor system with known topology and resistances.

It is important to calculated what the effects of a CME in a network can be. This is however complex and not done for realistic networks,

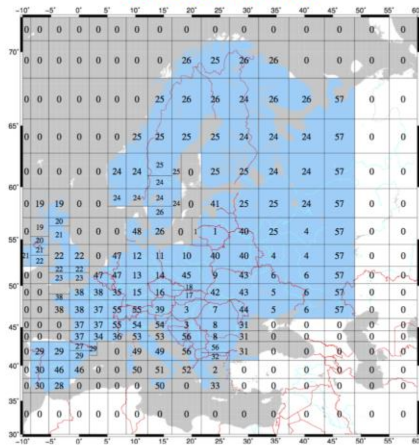
CONTINENTAL SCALE MODELLING OF GEOMAGNETICALLY INDUCED CURRENTS VILJANEN ET AL 2012

NETWORK

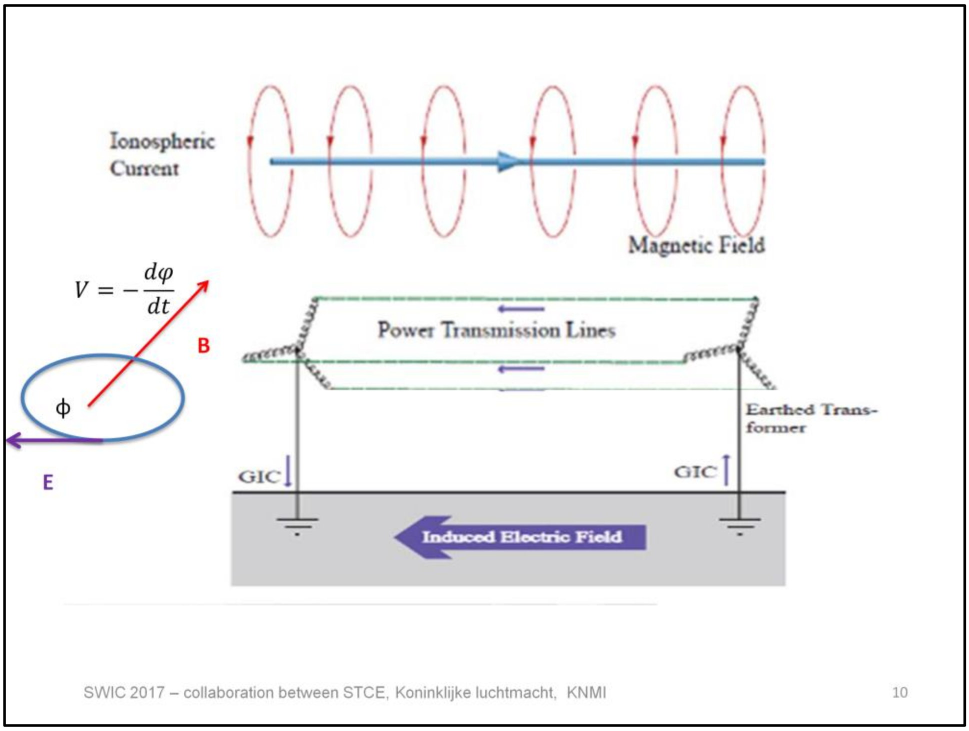


Prototype model of high-voltage power grids in Europe

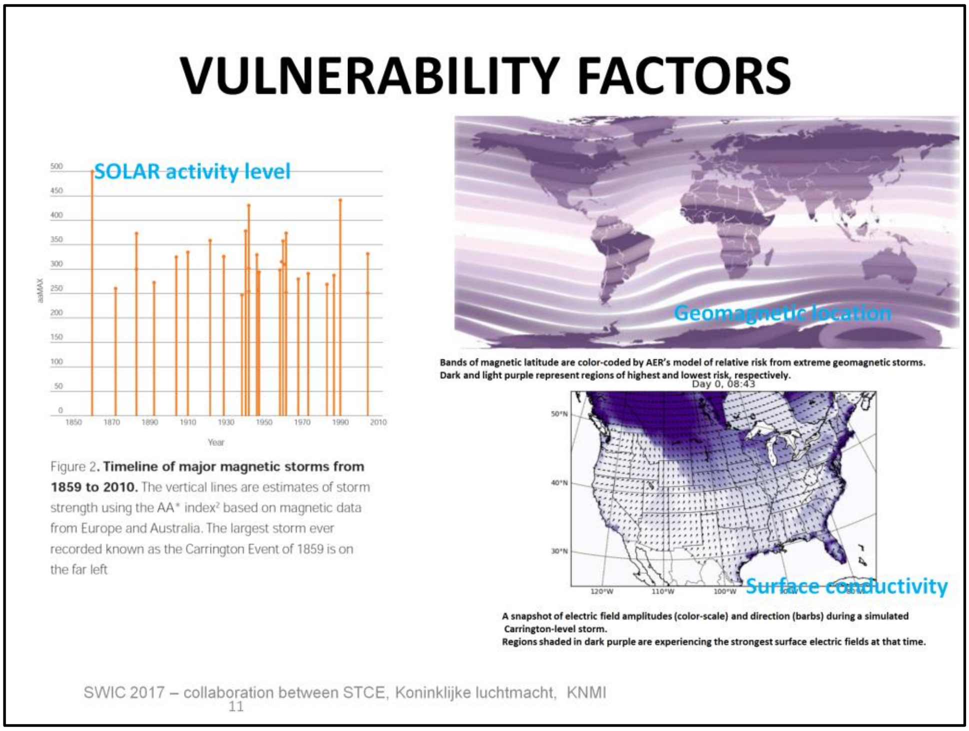
CONDUCTIVITY MAP



Map of conductivity blocks in Europe. Each number denotes a different 1-D ground model, whose parameters (layer thicknesses and resistivities) are listed on http://real.mtak.hu/2957/. Blocks outside of the presently modelled power grid are marked by 0.



The power grid inductively opposes the magnetic field change by the CME and generates a GIC through the Earth and the transmissionlines

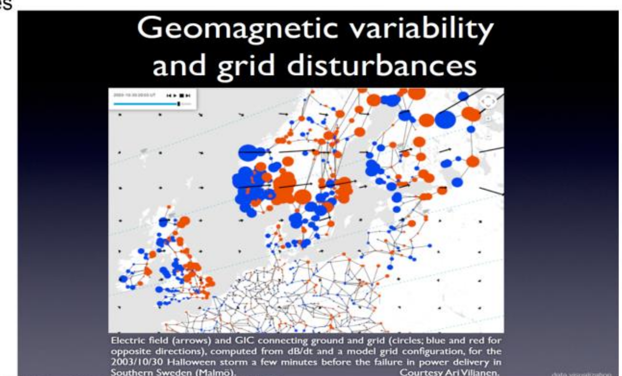


The risk of strong magnetic field fluctuations depends strongly on corrected geomagnetic latitude (Figure top left). During less severe magnetic storms, atmospheric currents are mainly confined to high magnetic latitudes and we associate them with visible aurora (e.g. “Northern Lights”). During extreme storms these currents are also found at lower latitudes, although still at a lower strength than the currents at high latitudes. Even regions of low magnetic latitude are not completely free of risk; for example, during the 2003 Halloween storm, transformers in South Africa sustained damage severe enough to remove them from service28. This magnetic latitude (35-45°) is equivalent to magnetic latitudes covering the Southern U.S. from California to Florida.

EFFECTS IN POWER GRIDS

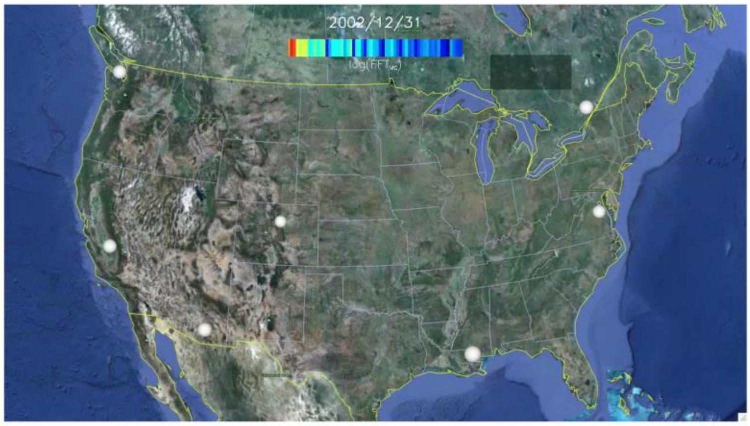
The variations occur at frequencies lower than 50 Hz so the generated current are quasi-direct and are superimposed on alternating current and can cause transformer cores to saturated halve of the cycle.

- **Damage to high voltage transformers**
  - Worst case: failure of transmission network
  - Long lead time for replacement of transformers
- **Voltage disturbances / line tripping**
  - Possible power outages



Electric field (arrows) and GIC connecting ground and grid (circles; blue and red for opposite directions), computed from dB/dt and a model grid configuration, for the 2003/10/30 Halloween storm a few minutes before the failure in power delivery in Southern Sweden (Malmö). Courtesy Ari Viljanen.

POWERGRID DISTURBANCES AMERICAN GRID
DUE TO SPACE WEATHER IN 2013



INDIRECT EFFECTS OF SPACE WEATHER

Note that there are three causes for disturbances

- Currents and dissipation in transformer increase and cooling oil sets fire
- The direct currents cause the alternating current in transformer to trip at one polarity
- The loss of GNSS time code causes phase disturbances in grid

Power grids are dependent on time code from GNSS to maintain grid components in phase: Phase is essential for grid infrastructures

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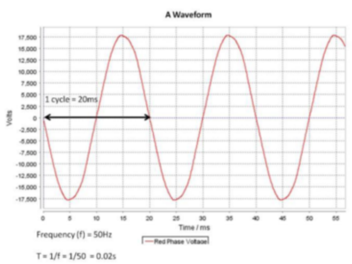

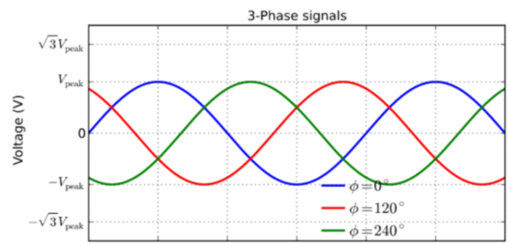

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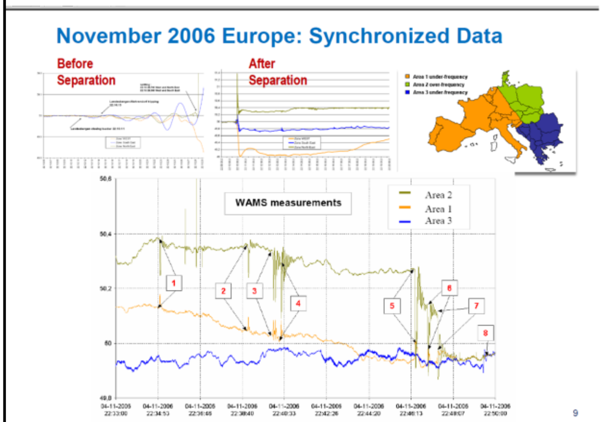
Here we discuss network breakdown because of loss of the timecode from GNSS so that network elements loose phase synchronisation

PHASE LOST IN EU NETWORK



In november 2006 phase coherence was lost in the European power grid.
The grid fragmented into three parts and Europe just escaped from disaster.
This event was not caused by Space weather but is indicative when time code from GNSS is lost to synchronise network components

MITIGATION/ADAPTATION MEASURES

- Remove long distances components from grid (break up grid in smaller pieces because self-inductance scales with system length
- Couple old networks in so current is distributed and current density, and hence dissipation goes down.
- Monitor phase
- Spare transformers

EUROPEAN NETWORK OF TRANSMISSION SYSTEM OPERATORS FOR ELECTRICITY ENTSO-E

- https://www.entsoe.eu/Pages/default.aspx

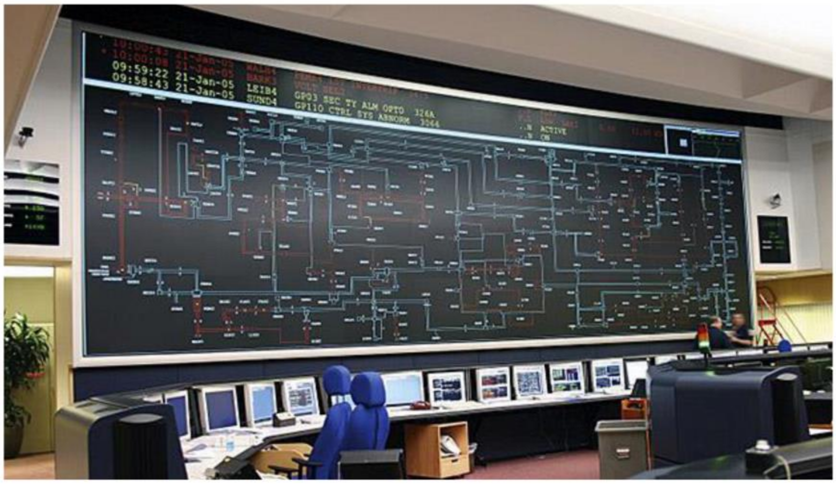
25 MB interactive map that containts the complete EU powergrid high/low voltage.

The electric field that drives the telluric currents has to be mapped on this grid to calculate the induced voltages

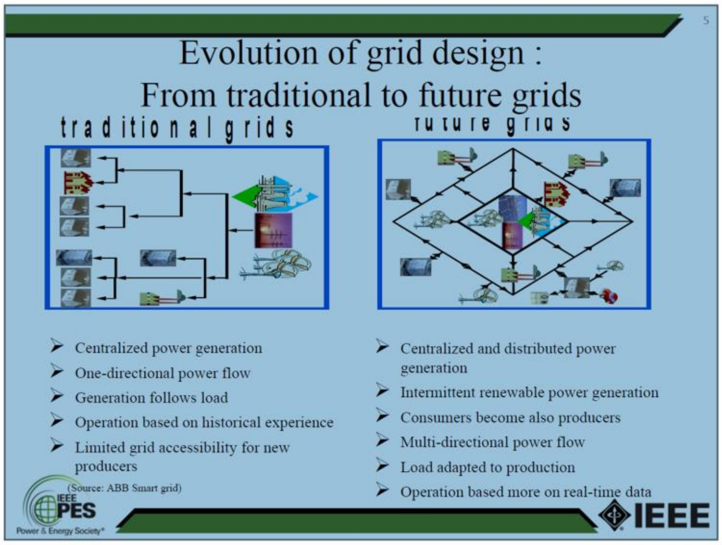
This is the real European electric power network

MONITORING PHASE

WIDE AREA MONOTORING SYSTEM (WAMS)



NEW GRID TOPOLOGIES



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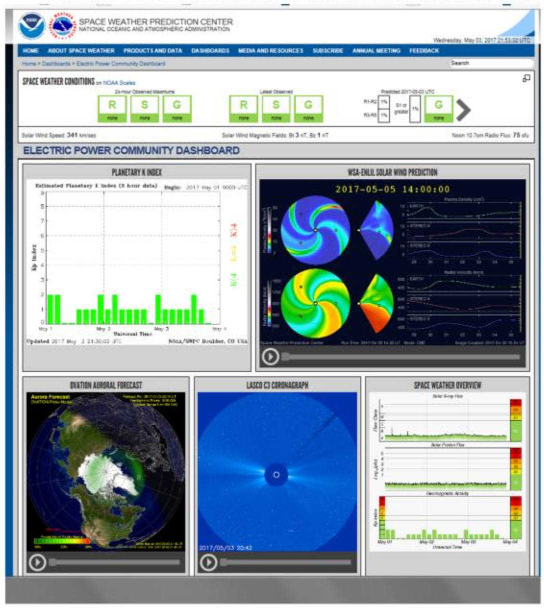
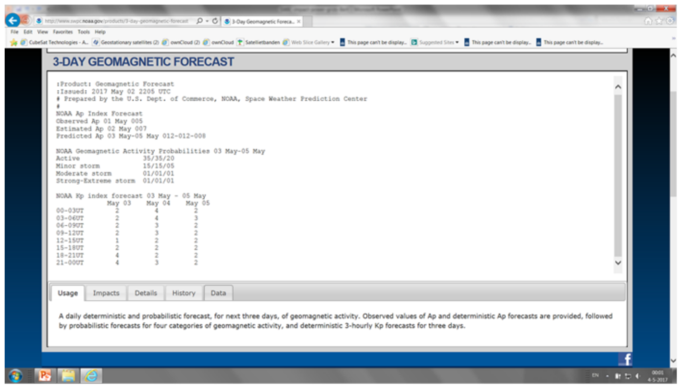
New network topologies or local energy production reduce the risk of space weather effects

NOAA ELECTRIC POWER DASHBOARD



NOAA Electric power dashboard

IMPORTANT FORECAST



GEOMAGNETIC STORM SCALES

G 5	**Extreme**	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	**Severe**	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	**Strong**	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	**Moderate**	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	**Minor**	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)