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Static electricity measurements for lightning warnings - an exploration

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1 Introduction

Lightning can have a major impact on operations at airports. At Amsterdam Airport Schiphol (AAS), the current lightning warning system is based mainly on the detected lightning strikes.

The lightning detection system in The Netherlands is called FLITS (Flash Localization by Interferometry and Time of arrival System). It detects the electromagnetic radiation from lightning discharges using detection masts equipped with five dipole antennas. Four of such detection masts are situated in the Netherlands and information from three similar masts in Belgium and constitute the lightning detection network. Signals in two frequency ranges (VHF and LF) are detected. Combining these two, the location of the discharge can be determined with an accuracy of about 1 km. An indication on whether the discharge was a lightning strike or a cloud-to-cloud discharge is also possible. More details can be found in Boonstra (2008).* At Amsterdam Airport Schiphol, a human observer also reports the occurrence of lightning discharges (in addition to FLITS).

When electrical discharges are observed or forecast, the meteorologist will report this during the regular briefing to AAS using colour codes. The Airside Operation Manager (AOM) will be informed as early as possible, preferably 1.5 to 2 hours in advance. Code Yellow is issued when discharges are observed (or forecast) in the Amsterdam Flight Information Region (FIR). Code Amber is issued when discharges occur between 5 and 10 km from the touchdown zone of runway 24 of the airport. Code Red is issued when the discharges occur within a 5 km radius. In the latter situation, the AOM can take precautions by deciding to halt ground operations such as refuelling. When the discharges have left the airport and are not expected to return, the meteorologist contacts the AOM, the status is changed to Code Green and in most cases the AOM decides to return to normal operation.

Thus the current lightning warning system is largely based on detected lightning strikes. This is a reactive process: lightning has to occur (within a certain distance) before a warning can be given. This has a potential danger that if the first strike occurs on site, no warning has been given.

The ideal situation would be to have a system in place that can predict the location of a lightning strike within a certain time frame. Unfortunately, no such system exists at the moment.

Various attempts are made to address this issue. For example, “Preflits” is a tool under development to forecast lightning in a shower before it actually occurs. Three-dimensional radar information is used to identify the chance of a shower producing lightning within the next 20 minutes (see *e.g.* Mosier, 2011). This system is still being tested, but first results are encouraging.

A probabilistic thunderstorm forecasting system, based on model output statistics (MOS), is used by the meteorologists to help them to predict if (severe) thunderstorms occur or not. In this system the Netherlands are divided into 12 regions of about 80 km x 90 km. For each region the probability of (severe) thunderstorms is predicted for 6-hour periods, out to 48 hours in advance. Verification shows that the skill of the MOS thunderstorm forecasting system is good. Because this system forecasts the probability of (severe) thunderstorms for a large area (80 km x 90 km), it is less useful for a point forecast, such as for Amsterdam Airport Schiphol.

Measuring the atmospheric static electric field may be another way forward to address the issue of forecasting lightning. In and near a developing thunderstorm, the atmospheric static electric field strengths increases. If this increase is detected, it may be used to produce lightning warnings. So called Electric Field Mills (EFM) can be used to measure the strength of the static electric field. The Airport Cooperative Research Program report from 2008 (ARCP, 2008) states on this

* KNMI is currently considering replacing FLITS. Various options to acquire lightning data are considered.

subject: "... *Electric field measurements will not, however, necessarily predict all nearby lightning strikes, and can be expected to produce occasional false alarms...*".

This report investigates the suitability of using field mills for lightning warnings based on information that is available from literature, manufacturers and users.

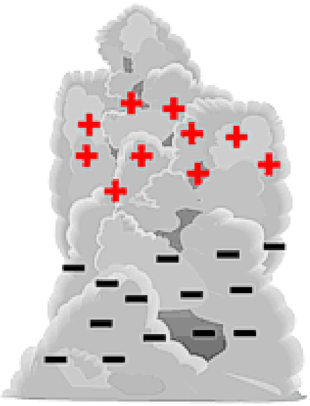
2 Background: lightning and the atmospheric electric field

The following background on lightning is adapted from information available at the website of the National Weather Service (NWS, 2012).

The conditions needed to produce lightning have been known for some time. However, exactly how lightning forms has never been verified so there is room for debate. Leading theories focus around separation of electric charge and generation of an electric field within a thunderstorm. Recent studies also indicate that ice, hail, and semi-frozen water drops known as graupel are essential to lightning development. Storms that fail to produce large quantities of ice usually fail to produce lightning.

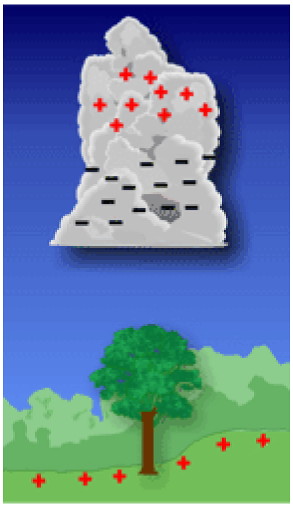
Forecasting when and where lightning will strike is not yet possible and most likely never will be.

Charge separation



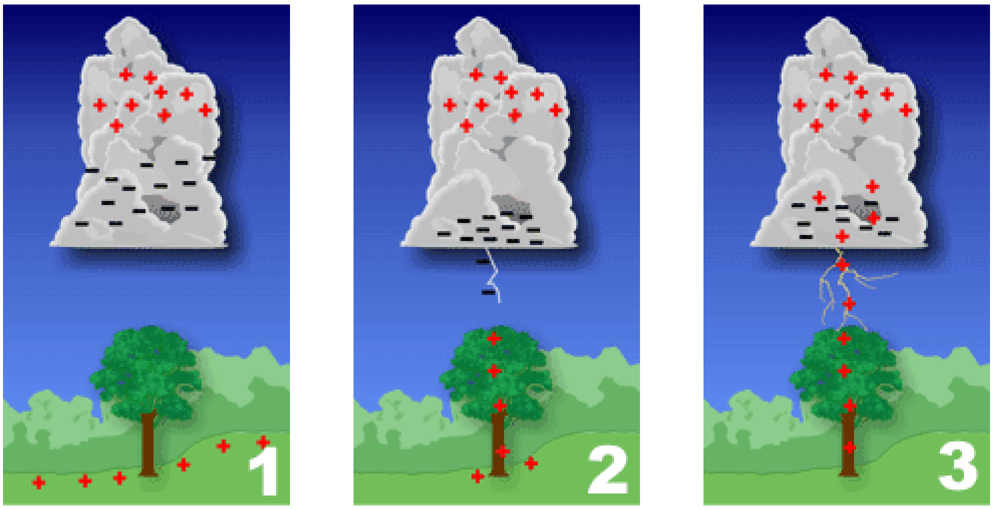
Thunderstorms have very turbulent environments. Strong updrafts and downdrafts occur with regularity and within close proximity to each other. The updrafts transport small liquid water droplets from the lower regions of the storm to heights between 35,000 and 70,000 feet, miles above the freezing level. Meanwhile, downdrafts transport hail and ice from the frozen upper regions of the storm. When these particles collide, the water droplets freeze and release heat. This heat in turn keeps the surface of the hail and ice slightly warmer than its surrounding environment, and a "soft hail", or "graupel" forms. When this graupel collides with additional water droplets and ice particles, a critical phenomenon occurs: Electrons are sheared off of the ascending particles and collect on the descending particles. Because electrons carry a negative charge, the result is a storm cloud with a negatively charged base and a positively charged top.

Field generation



As positive and negative charges begin to separate within the cloud, an electric field is generated between its top and base. Further separation of these charges into pools of positive and negative regions results in a strengthening of the electric field.
However, the atmosphere is a very good insulator that inhibits electric flow, so a tremendous amount of charge has to build up before lightning can occur. When that charge threshold is reached, the strength of the electric field overpowers the atmosphere's insulating properties, and lightning results.
The electric field within the storm is not the only one that develops. Below the negatively charged storm base, positive charge begins to pool within the surface of the earth (see image left). This positive charge will shadow the storm wherever it goes, and is responsible for cloud-to-ground lightning. However, the electric field within the storm is much stronger than the one between the storm base and the earth's surface, so most lightning (75-80%) occurs within the storm cloud itself.

How lightning develops between the cloud and the ground
A moving thunderstorm gathers a pool of positively charged particles along the ground that travel with the storm (image 1 below). As the differences in charges continue to increase, positively charged particles rise up taller objects such as trees, houses, and telephone poles.



A channel of negative charge, called a "stepped leader" will descend from the bottom of the storm toward the ground (image 2). It is invisible to the human eye, and shoots to the ground in a series of rapid steps, each occurring in less time than it takes to blink your eye. As the negative leader approaches the ground, positive charge collects in the ground and in objects on the ground.
This positive charge "reaches" out to the approaching negative charge with its own channel, called a "streamer" (image 3). When these channels connect, the resulting electrical transfer is what we see as lightning. After the initial lightning stroke, if enough charge is leftover, additional lightning strokes will use the same channel and will give the bolt its flickering appearance.

Positive lightning
The previous section describes what is called "negative lightning", because there is the transfer of negative charge from the cloud to the ground. However, not all lightning forms in the negatively charged region under the thunderstorm base.

Some lightning originates in the cirrus anvil or upper parts near the top of the thunderstorm, where a high positive charge resides. Lightning that forms in this region follows the same scenario as previously described, but the descending stepped leader will carry a positive charge while its subsequent ground streamers will have a negative charge. These bolts are known as "positive lightning" because there is a net transfer of positive charge from the cloud to the ground.

Positive lightning makes up less than 5% of all strikes. However, despite a significantly lower rate of occurrence, positive lightning is particularly dangerous for several reasons. Since it originates in the upper levels of a storm, the amount of air it must burn through to reach the ground usually much greater. Therefore, its electric field typically is much stronger than a negative strike. Its flash duration is longer, and its peak charge and potential can be ten times greater than a negative strike; as much as 300,000 amperes and one billion volts!

Some positive strikes can occur within the parent thunderstorm and strike the ground beneath the cloud. However, many positive strikes occur near the edge of the cloud or strike more than 10 miles away, where you may not perceive any risk nor hear any thunder.
Also, positive flashes are believed to be responsible for a large percentage of forest fires and power line damage. Thus, positive lightning is much more lethal and causes greater damage than negative lightning.

Positive lightning can be the dominate type of cloud-to-ground during the winter months and in the dissipating stage of a thunderstorm.

3 Electric Field Mills

The atmospheric static electric field can be measured using so-called Electric Field Mills (EFM).

Measurement principle
Electric Field Mills measure the static atmospheric electric field at the location of the instrument. They work by alternately exposing a sensor element to the electric field and an uncharged reference. The sensor element is charged by the external electric field, and subsequently discharged when exposed to the uncharged reference. The induced charge of the sensor element is converted to a voltage using charge amplifiers, and this voltage is proportional to the external electric field.

In most commercially available field mills, a rotating shutter is used for the exposure and shielding of the sensing element. A schematic picture of this type of instrument is shown below (Hill, 1999).

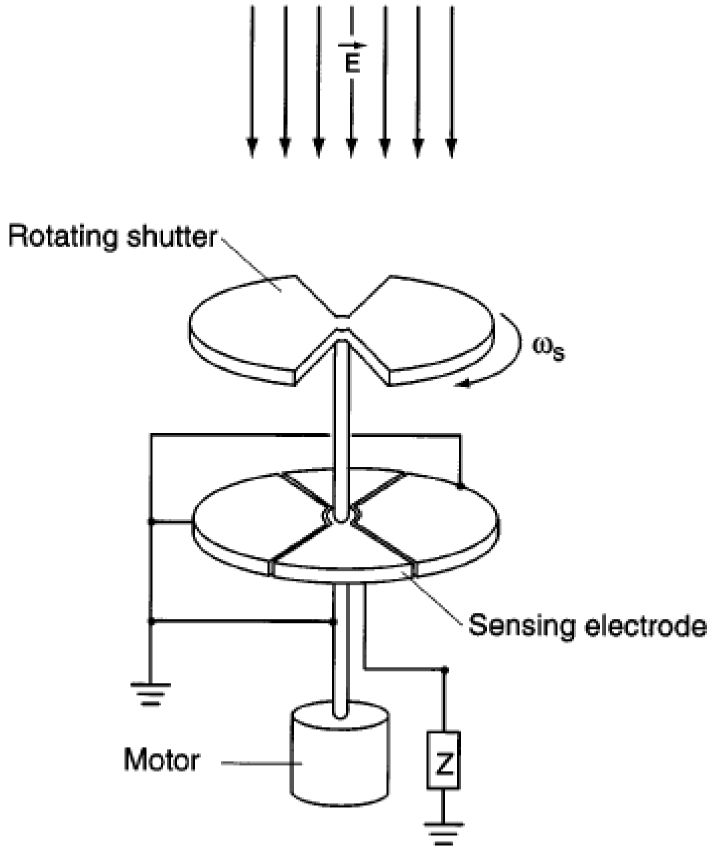


Figure 1. Schematic of a shutter-type electric field mill.

Measurements
An example of field mill measurements can be seen in Figure 2, where data from a field mill at high altitude in the Austrian Alps is shown. Here the electric field strength varies between + and – 5000 V/m. This example also shows that the field strength can vary several thousands V/m within minutes. Generally, data are collected at about a 1 s time resolution, although other values are used as well.

Range
Since field mills measure the local atmospheric electric field, they have a limited range with respect to area for which the resulting lightning warnings are valid. This range also depends on the exact location, and is influenced by matters such as orography, surface type, nearby buildings,

vegetation etc. Typical values (from the manufacturers and literature) range from a few km up to about 20 km.

Warning levels
The local electric field varies from location to location, even without a thunderstorm nearby. Matters such as orography, surface type, nearby buildings, vegetation etc. all have an influence on the measured electric field. This means that the strength of the local electric field above which a warning is given also varies between locations. Thus, this trigger level needs to be set individually for each location. This can be done based on the measurements. It is very difficult to calibrate a field mill for absolute measurement of static electric field, because of the influence of the surrounding structure and local enhancement or attenuation. For warning purposes absolute values are not required.

Installation
Field mills operate more reliable if they are installed with the sensor element looking downwards. The location must be chosen carefully, since many variables can influence the local electric field. The area must be flat, without vegetation, free of objects that change position (e.g. humans, animals), without even small metal fences, away from aerosols, dust, exhausts, etc... Installation at roof tops is possible, and has advantages and disadvantages. The instrument manuals provide guidance in these matters.

Suppliers/Manufacturers
There are a number of manufacturers supplying Electric Field Mills. They are listed below. Details on the EFM's can be found in the Appendix.

- *Campbell Scientific*, UK
  Instrument: CS110
  Campbell field mills are used quite widely. One of the users that have been found willing to share their experiences (see chapter 4), uses this instrument.

- *Vaisala*, Finland
  Instrument: EFM 550
  Vaisala uses the EFM 550 in combination with data from the lightning detection network in the Vaisala Thunderstorm Warning System TWX300. The field mill is also available separately. For lightning warnings, Vaisala recommends to use other data sources alongside the field mill.

- *Boltek*, USA
  Instrument: EFM-100
  A company specialized in lightning detection. They sell three types of lightning detectors, and the EFM-100 field mill.

- *Mission Instruments*, USA
  Instrument: EFS-1001 / Zebra (lower specifications)
  Mission instruments is a sensor manufacturer. They do not sell complete lightning warning systems, although their field mills can be part of such systems. Also, they do not (yet) have CE or any other certification for the European market.

- *Prévention Foudre Service*, France
  This company has recently been closed down, and is not considered any further

4 User experiences with field mills for lightning warnings

Field mills are used by various user groups for lightning warnings. Applications range from airports, military, outdoor events (e.g. golf courses, concerts) to meteorological institutes. Some use the instruments stand-alone, whereas others use them in combination with other data *e.g.* a lightning detection network and/or with human supervision.

Below the user experiences obtained during this investigation are given. They are summarized in chapter 6.

ZAMG – Austrian Meteorological Institute

Gerhard Schauer from ZAMG has kindly provided the following information.

"*ZAMG uses a field mill at the mountain station Sonnblick (3105 m asl) in the Alps. This site is frequently in the clouds and lightning may occur even if there is no thunderstorm activity around. Therefore lightning location systems can not be used for issuing warnings at this site.*
The real-time data are available at http://www.sonnblick.net/portal/content/view/20/224/lang,de/ (lowest diagram).

The Campbell CS110 field mill has been in use for about 1 year. The sensor is being optimized to allow lightning warnings in advance, and for lightning detection.

For case studies and optimization of the software data from the official lightning detection network in Austria (ALDIS) is used, along with 3 local lightning sensors measuring direct flashes into the tower of the observatory and the cable of the cable car.

As an example, two cases are shown in Figure 2. † *The first example (top panel, 22 June 2012) shows a situation with active warning and three very close strikes (at 22:38:52, 22:45:46 and at 22:51:25 UTC). The second case (lower panel, 23 June 2012) shows a false alarm situation between 5:46 and 6:24, without any strike. Although the field was up to 5000 V/m!*

Currently, the warning criteria are as follows: the warning threshold is +/-2500 V/m. Also, the warning gets activated when lightning strikes were identified by the field mill even at lower voltage levels. When the voltage drops below +/- 2000 V/m and no lightning strikes were detected, both for approx. 5 min, the warning is stopped again. These criteria may change somewhat after more evaluation has been done.

Up to now, no alarm performance analysis has been done. This also depends on the criteria that are defined.

The field meter itself works very good, without any troubles or issues. The instrument is still clean and there was no need for any maintenance.

It is very difficult to calibrate a field mill for absolute measurement of static electric field, because of the influence of the surrounding structure and local enhancement or attenuation. For warning purposes absolute values are not required.

For all weather operation field mills with the sensor elements looking downward are more reliable than field mills looking upward. Heating for winter operation may be useful."

† Note from the author: a spike followed by decrease of field strength and sometimes a change in polarity indicates lightning discharge. Afterwards the field strength recovers again.

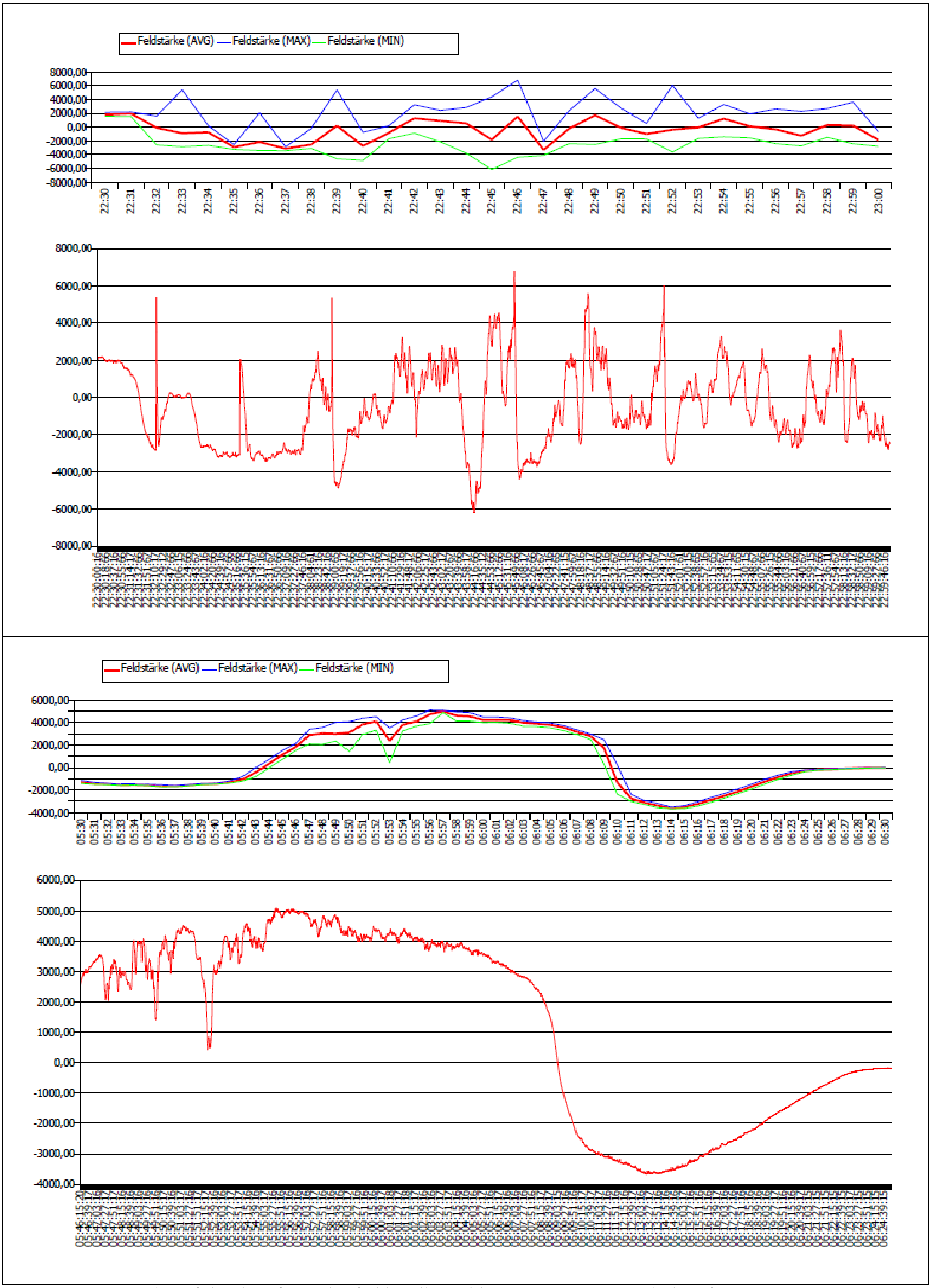


Figure 2. Examples of the data from the field mill used by ZAMG. Top panel: data from 22 June 2012, lower panel: data from 23 June 2012. The upper part of the plots show the 1 - minute averaged EFM field strength in V/m (red line), the minimum (green line) and maximum (blue line) within this minute. The lower part of the plots show the data at 500 ms time resolution. Here, the peaks in signal indicate when lighting occurred.

Company‡, United States

Part of this US company deals with commercial weather forecasts. The director of meteorological operations has kindly agreed to share his experiences in using electric field mills. These are used in the forecast services for a series of outdoor events in the US. The field mills are part of a comprehensive package for on-site meteorological support. The user experiences are given below.

"I have a team of meteorologists that travel around the western hemisphere to the outdoor events, providing real-time weather support centered around lightning safety.

The meteorologists interpret the real-time information from the EFM to determine when the electric field has reached an unsafe level. What my team does is analyze the information and provide a professional recommendation to the event organizers that the local area is entering a dangerous situation due to lightning and must evacuate to safety.

The addition of an EFM is necessary to measure the atmospheric electric field and how it is changing over time. These field measurements assist the on-site meteorologists in accurately predicting the very difficult 'first-stroke' as the charge builds to levels that can no longer be sustained without electrical discharge. Additionally, once lightning activity has occurred and is being monitored, the EFM also provides valuable information on when the local charge is no longer present in the near-course vicinity, thus enabling play to resume as soon as possible.

My team utilizes lightning detection data from a network for plotting the location and distance of the lightning from their location. This lightning detection data is particularly useful in monitoring thunderstorms that maintain their history of lightning activity and have consistent movement.

We have been using the current type of EFM for 7 consecutive years. We have 9 individual EFM's that rotate through a schedule of 100+ events.

We have been very pleased with the performance and durability of this EFM. Since the events move around week-to-week, the equipment must be durable to withstand the excessive travel.

I do not have any formal metrics on the EFM. There have been times where the EFM picked up lightning discharges that were not displayed by the lightning detection network, making it a better tool for real-time lightning detection. I have never missed a lightning occurrence with the EFM. It will always plot lightning discharges and the associated electric field variances within 5-7 miles of your location. I have actually had occurrences where lightning was accounted for as far as 20 miles away. There is a downside to this. The EFM does not display distance, location, or type of lightning strike, while the lightning detection network will showcase that.

Overall, in my opinion, the EFM equipment does an outstanding job of showcasing when conditions are building up to and decreasing from a lightning event. This tool should be incorporated into a suite of other meteorological information such as a real-time lightning display, radar, satellite, local observations, etc. I would not recommend the use of this equipment by a novice. Someone with a sound understanding of the atmosphere, specifically convective initiation should be the operator."

‡ Since some of the details of the original information are confidential, this contribution has been made anonymous by the author. The essence of the user experience has not been altered by this.

Greater Toronto Airport Authority; Toronto Pearson Airport, Canada

Jason Noble works at Toronto Pearson Airport as a Meteorologist/Senior Environmental Officer in the Environmental Stewardship Division.. Dan Elliot is Manager Radio & Wireless Telecom in the Operations and Customer Experience division of the airport. Together, they have kindly supplied user information.
Three military-grade field mills are used at the airport within the Vaisala TWX 300 lightning warning system. This combines lightning detection data with the field mill data (see Figure 3). The electric field strength is not interpreted separately by the meteorologists. Below, the answers they have given to a number of questions are shown in *italics*.

- How do you use the field mills?
  - Am I correct in assuming that the colour coded warnings are for the airport area? Red meaning: personnel being moved indoors, no refuelling, etc?

Correct, "RED" means cloud to ground lightning within the 8km Ring (noted we use 8, 16 and 50km warning zones). Fuelling is to stop and its advised to clear the field.

  - Do you also use the field mill output (electric field strength) directly? As in: being interpreted by a meteorologist?

*Below is the LDS logic used for Toronto Pearson Airport (within the TWX 300 system) (*see Figure 3*).*

The electrical field strength is not interpreted.

Statistical outputs can be generated or created by the system.

For a red RAD (remote alarm display) indicator / strobe activation, stakeholders have created and implemented safety procedures for their employees.

FOREWARN[SM] PRECISION LIGHTNING WARNING SYSTEM

REMOTE ALARM DISPLAY SYSTEM - OPERATING PROFILE

LESTER B. PEARSON INTERNATIONAL AIRPORT (YYZ)

R A D INDICATION	CRITERIA	ACTIVITY SUMMARY
GREEN	No **lightning*** detected within 50 km *and* all Field Mills are reading below alarm threshold.	No activity is indicated.
YELLOW & GREEN	**Lightning*** detected within 50 km *or* One EFM has reached or exceeded alarm threshold	Conditions favor development of thunderstorms, **or** One or more storms are nearby and are either active or undergoing development
YELLOW	**Lightning*** detected within 16 km *or* **Lightning*** detected within 50 km and one or more field mills have reached or exceeded alarm threshold *or* Two or more field mills have reached or exceeded alarm threshold.	Activity is close to the field.
RED & YELLOW	**Lightning*** detected within 16 km *and* one field mill has reached or exceeded alarm threshold	Activity is close enough that a red light can be anticipated, **or** If red status was previously displayed, then the storm is beginning to display less influence on the local area.
RED	**Lightning*** detected within 8km *or* **Lightning*** detected within 16 km *and* any two or more field mills have reached or exceeded alarm threshold.	Lightning* detected in the local area. Strobes activated and callout performed.
LIGHTS FLASHING LAST INDICATED CONDITION	RADS has failed to receive a message from the PLWS Alarm System during last 30 seconds. Failure may be due to loss of power, phone line, modem system, PLWS workstation or satellite system.	Disregard system status messages until lights stabilize. Perform System Troubleshooting if return to normal function does not occur within one minute.
FLASHING RED & GREEN	System is re-synching after initiating a reset command, *or* The entire system has been reset by the PLWS workstation.	Disregard system until normal light sequence returns. Perform System Troubleshooting if return to normal function does not occur within one minute.

ALL DISTANCES ARE IN KILOMETERS MEASURED FROM A POINT LOCATED 0.74 KM WEST OF T-1.

FIELD MILL THRESHOLD → 2250 V/M

ALARM DELAY → 5 MINUTES

LIGHTNING* (definition) → CLOUD TO GROUND

Modified: Oct, 03, 2006 ver: 9

Figure 3. Colour coded warning system in place at Toronto Pearson Airport, using the Vaisala TWX 300 system.

- Do the field mills have added value in the generation of the lightning warnings?

Yes, 90% of the data is from Environment Canada and the National Weather Service (due in part to our close proximity to the Canada US Boarder. The 10% is very important in that it provides immediate real time field level data. Effectively if we lost the feed to the Weather Service Data we could continue to operate with the field mills with assurances that we have the local campus data. We use 3 field mills in a triangular formation, south northeast corner and northwest corner. Most of the weather approaches from the west, but on occasion we can have weather approach from the south or east.

- Has there been any analysis done on this? E.g. statistics such as False Alarm Rate, Probability Of Detection etc, with and without using field mills? Are there maybe any reports on this?

The LWS System records all data and holds as Historical data, we do need to archive annually. We have not taken action to measure accuracy, however, it is within my plans to have Jason begin to measure accuracy of this and other data we receive beginning in 2013.

- Would you recommend using field mills at other airports?

Absolutely, as noted while only 10% of the data they provide the most immediate and local data available from a Health & Safety Perspective.

- You are one of the few airports (that I know of) that use field mills in their lightning warning system. Do you know why they are not more generally used at airports?

I am not sure on the comment "more generally used" of the airports I am familiar with using the TWX300 LS System most have at least one for that crucial Local immediate data.

And a few technical questions:

- I know you use a Vaisala system. Is that the TWX300? And the field mill is then the EFM550?

No we don't, we use a Military spec field Mill, we found the initial field mills that were a predecessor to the EFM550's where not as weather resistant to our cold and very changing conditions which resulted in freeze up of the units. We have also heated the one outside field mill cabinet.

- What is the range (as in: distance) of the field mills?

Noted they cover the immediate campus and outside the immediate boundaries.

- How long have the field mills been in use? Are you pleased with how robust they are?

Present field mills have been in service since 2007 and are very robust without a failure, we chose based on a very high mean time between failure rate that is proving itself. My feeling is they should be replaced or fully serviced every 8 – 10 years.

- Any other information you may think relevant is also very welcome!

I am available for questions or discussions. Thanks.

5 Literature study

Although field mills have been in use for quite some time, it is hard to find independent evaluation in the literature. Especially in the case where field mills are used in conjunction with a lightning detection network. Below, the few studies that have been found are summarized.

In the literature, skill scores (Kok, 2000) are used. These can be defined using a 2x2 contingency matrix which can be made for the results of each combination of "yes/no" events:

		Field mill warning y/n	
		Yes	No
Cloud-to-ground Lightning strike y/n	Yes	**a**: correct warning	**b**: missed events
	No	**c**: false alarm	**d**: correctly not warned

Each event is put in one of the four regions a to d of the matrix:
a: the field mill produces a warning and a cloud-to-ground strike occurs (correct warning)
b: the field mill does not produce a warning but a cloud-to-ground strike occurs (missed event)
c: the field mill produces a warning but a cloud-to-ground strike does not occur (false alarm)
d: the field mill does not produce a warning and a cloud-to-ground strike does not occur (correctly not warned)

The skill scores can now be expressed as a function of the number of events in the four regions of the matrix:

Probability of Detection (POD) = a/(a+b)
The POD indicates the fraction of the total number of cloud-to-ground lightning strikes that coincide with a warning from the field mill.
False Alarm Ratio (FAR) = c/(a+c)
The FAR indicates the fraction of the total number of warnings from the field mill that do not coincide with cloud-to-ground lightning strikes.

Note that the definition of coincidence depends on the range of lightning strikes from the location of the EFM. Also, the time interval used for classifying the events varies per evaluation, as does the warning threshold of the field mill.

Other useful parameters are:
Lead Time (LT): the time between the moment of warning is issued and the occurrence of a cloud-to-ground strike.
Delay Time (or Dwell Time) (DT): the time interval for which an issued lightning warning is valid. Different values for the dwell time are adopted in the literature.

ACRP (Airport Cooperative Research Program) Report 8, Lightning-Warning Systems for Use by Airports, Transport Research Board of the National Academies, 2008

This extensive report mentions the use of field mills only briefly. After making the distinction between lightning detection and lightning prediction, it states: "…*In some cases, however, a lightning storm may develop directly over an airport, and the very first strikes can put airport workers at risk. In this case, a prediction system may be able to provide a uniquely valuable warning. Even the best predictions only give a general indication that a lightning strike is likely to occur in the immediate vicinity. The timing and path of an individual lightning strike are, for all practical purposes, unpredictable…*".
And about measuring the electric field: "… *Electric field measurements will not, however, necessarily predict all nearby lightning strikes, and can be expected to produce occasional false alarms…*".

Cloud-to-ground lightning warnings using electric field mill and lightning observations, Murphy *et. al.*, 2008

This is a paper by Vaisala from the 20th International Lightning Detection Conference in 2008. They study the effectiveness of an automated warning system which combines data from the lightning detection network and two local field mills. Data from two summers in Florida, USA are used. They find that the Probability of Detection is poor (0.15 – 0.38), and the False Alarm Rate is high (0.71 – 0.78). Without using the field mills, these would be: POD = 0.67 and FAR = 0.68. They attribute these poor results to a number of reasons: the sizes of the area under investigation with respect to the range of the field mills, and the local environment in which the storms occur. Also, a relatively low trigger level was used for the field mills. In this study, DT was set at 10 minutes, LT was not determined.

Total lightning, electrostatic field and meteorological radar applied to lightning hazard warning, Montanyà *et. al.*, 2008

Another paper from the 20th International Lightning Detection Conference in 2008, this one by the Technological University of Catalonia and the Catalan Meteorological Service. In this paper, the various sources of lightning data are combined in order to find the best warning method. On the use of field mills, the conclusion is: "*It is not new that the measurement of the electrostatic field offers some idea of the electrical activity of a storm. However the application to warning is still not too much extended due to the complexity of the electrostatic field behaviour at ground level. In this paper we presented few ideas about how the electrostatic field could be combined with total lightning location information for warning purpose.*".

On the lightning hazard warning using electrostatic field: Analysis of summer thunderstorms in Spain, Aranguren *et. al.*, 2009

A paper in the Journal of Electrostatics from the Barcelona group (see previous paper). In this paper, two methods using electro static field measurement for lightning warnings are compared: the "traditional" method using an electrostatic field threshold, and a second method using the polarity change of the electrostatic field to produce the warnings. Seven summer storm cases from 2004 and 2006 are used. In the first method, the effective alarms, false alarms and failure to warn cases are determined for various electrostatic field thresholds, thus finding the optimum threshold. In this case, the POD is 0.37and the FAR is 0.88. For the second method, the POD is 0.47 and the FAR is 0.78. LT, the time between the first warning and the first lightning strike is on average 6.5 minutes in the first method and 8 minutes for the second method. This means that the storms are detected in short ranges. In this study, DT was set at 30 minutes.

Lightning risk warnings based on atmospheric electric field measurements in Brazil, da Silva Ferro *et. al.*, 2011

A paper from the Journal of Aerospace Technology and Management (a Brazilian techno-scientific publication), by the Institute of Aeronautics and Space from Brazil. In this paper, data for 2 summers of a single field mill situated in south-eastern Brazil at 800 m asl is analyzed. A lightning detection network is used as a reference for cloud-to-ground lightning strikes. The distance from the field mill and the warning threshold were varied, and optimum values were found: for a range of 10 km around the field mill, and a warning threshold of 0.9 kV/m, the POD is 0.60 and the FAR is 0.41. They mention that the local characteristics of the site are important factors, and that sensors installed at sea level can result in smaller POD because the distance to the centre charge of the cloud is larger. Also, since the height of the centre charge of the cloud varies with latitude, latitude will also influence the effectiveness of field mills for lightning warnings. LT was found to be 13 minutes in this study, and DT was fixed at 45 minutes.

6 Summary and conclusions

Summary

Aim

Traditional lightning warning systems are based on lightning detection, and are thus not able to generate warnings before the first lightning occurs. If a thunderstorm develops overhead, this can lead to the dangerous situation that the first lightning strike may occur on site without warning. As a means to predict this first strike, measuring the static atmospheric electric field may be a way forward. Therefore, this study investigates the effectiveness of lightning warnings by static electric field measurements.

Instrument

So-called Electric Field Mills (EFM) are used to measure the static electric field. They work by alternately exposing a sensor element to the electric field and an uncharged reference. In most commercially available field mills, a rotating shutter is used for the exposure and shielding of the sensing element. They can be used in lightning warnings in a range from a few km up to 20 km, depending on the local situation. Also the value of the static electric field above which a warning is issued is dependent on the local conditions.

Literature

There are few literature studies on the use of static electric field measurements for lightning warnings. These studies indicate that electric field measurements will not necessarily predict all nearby lightning strikes, and can be expected to produce occasional false alarms. The few studies that have looked into the effectiveness of using of static electric field measurements for lightning warnings find Probabilities Of Detection (the fraction of correctly predicted strikes) between roughly 0.20 and 0.60, and False Alarm Rates (the fraction of warnings which were not followed by strikes) between roughly 0.40 and 0.80. All these papers emphasize that these numbers depend strongly both on the exact local situation, and on the electrostatic field threshold which is chosen as warning level.

In these studies, the dwell time for which a lightning warning is issued ranges from 10 to 45 minutes. The lead time between the moment of warning and the occurrence of a cloud-to-ground strike varies between 6 and 13 minutes (when strikes do occur), but this was only determined in 2 studies.

User experiences

Three users have been identified who use field mills for lightning warnings: one using a single field mill in the Alps, one using multiple field mills at changing locations (outdoor events) in combination with various other meteorological sources of information and the third using three field mills in combination with a lightning detection system at an airport (using the Vaisala TWX 300 system).

The first two users indicate that not all lightning strikes are predicted, and that false alarms occur. Unfortunately, none of the three users have done a statistical analysis on the effectiveness of the lightning warnings.

All users mention that they are indeed using the field mill data and feel that they are useful in producing lightning warnings. The user at the airport state that the data is particularly useful as it is providing very local and real time data.

Two users state that the electric field level above which a warning is given is very dependent on the local situation and needs to be set for each instrument individually.

One of the user states that only someone with a sound understanding of the atmosphere, specifically convective initiation, should be the operator.

All users are pleased with how robust the instruments are, and the instruments require little maintenance.

Suppliers/Manufacturers
Four suppliers of electric field mills have been found: Campbell, Vaisala, Boltek and Mission Instruments. None of the suppliers have been able to indicate POD and FAR for lightning warnings. As a reason, they state that this depends on too many variables, such as warning threshold, size of the area for which the warning is valid, lead time between a warning and a lightning strike etc. The instruments differ in detailed specifications, life times, prices etc, but overall they seem (on paper) fairly similar. In the current investigation, the detailed differences between the instruments are not relevant.

Conclusions

Field mills have been around for a long time, but have only relatively recently been used for lightning warnings. An increase in the atmospheric electric field at ground level indicates a potential for lightning (strikes), but this is not always followed by lighting itself. Also, not every lighting strike is preceded by an increase in the atmospheric electric field at ground level.

This is reflected in the statistics from the literature. When using Electric Field Mills for lightning warnings, the Probability Of Detection is rather poor: values between 0.2 and 0.6 have been reported in the literature. Similarly, the False Alarm Rate for lightning warnings is quite high: between 0.4 and 0.8. The area for which a warning is valid varies with the local conditions and the sensor used and ranges from a few kilometres up to about 20 km.

Several different sources recommend using other meteorological information alongside field mills to produce lighting warnings. These can be lightning detection networks, weather radar data, weather model output etc. This would require a well-trained meteorologist to interpret the information. Some also use the field mill for the detection of lighting strikes.

The electric field level above which a warning is given is highly dependent on the local situation and needs to be tuned for each field mill individually. Also, the range of the instrument strongly depends on the local situation.

The added value and effectiveness of field mills in lightning warnings at Amsterdam Airport Schiphol cannot be quantified from the information currently available. The rather poor Probability Of Detection and quite high False Alarm Rate values reported in the literature suggest that the added value will be small. The studies, however, give no separate scores for “first strike” events. In fact statistics on the number of “first strike” events at Amsterdam Airport Schiphol are not available and need to be considered in relation with the effectiveness of the current and future lightning detection system. It should also be noted that field mills give no information on the distance of expected lightning strikes, hence Codes Amber and Red cannot be distinguished by using field mills.

7 References

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8 Appendix

In this appendix, the detailed information about the field mills provided by the four manufacturers is reported. Additional information is available in brochures and manuals.

	Campbell Scientific CS110	
		remarks
Type	Reciprocating shutter	
Measurement quantity	Electric field strength (V/m)	
Range of measurement quantity	± 22300 V/m	
Measurement accuracy	5 % of reading + 8 V/m offset	
Measurement resolution	0.32 V/m (0 - 2200 V/m), 3.2 V/m (>2200 V/m)	2 input ranges
Drift/stability	drift negligible over a 2-year period	
Time resolution/averaging/response time	sample rate programmable, down to 5 Hz	
data output	CR1000 data logger required	data logger used for measurement and control functions, data processing and storage, user interface language, communications options
power supply	11 - 16 VDC	
power consumption	max 9 W	
Calibration	factory calibration, site correction	
	interval between 1 - 3 years	
MTBF		
MTTR		
life time	5 - 10 years with regular maintenance/calibration	
maintenance	checks, cleaning, calibration	
maintenance interval	once per year	
Use in lightning warnings	Y	can be used with "strike guard" lightning detection
Available separately from lightning detection	Y	
Effective range for lightning warning		
POD for lightning warnings (CG)		
FAR for lightning warnings (CG)		
Refs for lightning warnings		
Price indication	4000 euro	
Users (for lightning warnings)		

	Vaisala EFM550	
		remarks
Type	Rotating shutter	
Measurement quantity	atmospheric electric field	
Range of measurement quantity	± 10 kV/m	
Measurement accuracy	± 5 % of reading	± 10 % in manual, Vaisala is looking into this
Measurement resolution	1 V	
Drift/stability	not specified	
Time resolution/averaging/response time	time resolution 2 s, sample rate 10 Hz, response time 1 s	
data output	RS232, binary format	
power supply	110 - 240 VAC, or 20 -30 VDC	
power consumption	2.3 W	
Calibration	factory service once/three years	
MTBF	25000 h (for electric motor)	
MTTR		
life time		
maintenance	factory service once/three years	
	cleaning once/6 months in harsh environments, less frequently in other	
maintenance interval	see above	
Use in lightning warnings	Y	
Available separately from lightning detection	Y	
Effective range for lightning warning	about 5 km as an estimate	
POD for lightning warnings (CG)		
FAR for lightning warnings (CG)		
Refs for lightning warnings		
Price indication	USD 12360	
Users (for lightning warnings)		

	Boltek EFM-100	
		remarks
Type	Rotating shutter, a rotor spins blocking/unblocking the field from 6 sensors	
Measurement quantity	Electric field in kV/m	
Range of measurement quantity	± 20kV/m	
Measurement accuracy	5% +/-0.05kV/m	
Measurement resolution	0.01kV/m (digital output)	
Drift/stability	Calibration is only needed at time of assembly	
Time resolution/averaging/response time	0.1 s	
data output	Electric field in kV/m, digital and analogue	
power supply	120 or 220 VAC, or 12 - 15 VDC	
power consumption		
Calibration	Calibration is only needed at time of assembly	
	Calibration is done at +20kV/m and -20kV/m	
MTBF	7 years	
MTTR		
life time	7 years	
maintenance	Cleaning debris from around rotor	
maintenance interval	Every 6 to 12 months	
Use in lightning warnings	Y	
Available separately from lightning detection	Y	
Effective range for lightning warning	0 to 24 miles	
POD for lightning warnings (CG)		
FAR for lightning warnings (CG)		
Refs for lightning warnings		
Price indication	Price starts at $1999 USD, and goes up if longer than 100' cable lengths are needed	
Users (for lightning warnings)		

	Mission Instruments EFS-1001	
		remarks
Type	Rotating shutter	
Measurement quantity	electric field, V/m	
Range of measurement quantity	± 20 kV/m	
Measurement accuracy	at best 1% error	highly dependent on installation and calibration
Measurement resolution	0.6 V/m	
Drift/stability	<< 5 % in 10 years	occasional cleaning required
Time resolution/averaging/response time	10 Hz	
data output	electric potential gradient (V/m)	
	RS232 output available	
power supply	120 -240 VAC, or 20 - 30 VDC	
power consumption	8 W	
Calibration	sensor calibration in Mission's laboratory	calibration interval depends on environment (contaminants,
		insects etc). Build-in test generator indicates need for calibration.
	site calibration if site is not "ideal"	
MTBF	300000 hours	
MTTR	< week, < 24 hrs by special request	
life time	25 years	
maintenance	cleaning of parts	duration 0.5hour
maintenance interval	6 months (coastal environments) - 3 years (dry env.)	the build-in test generator indicates need for cleaning
Use in lightning warnings	Y	
Available separately from lightning detection	Y	
Effective range for lightning warning	5 - 8 km as an estimate	
POD for lightning warnings (CG)		Mission is a sensor manufacturer. So field mills produce
FAR for lightning warnings (CG)		electric field data, not lightning warnings.
Refs for lightning warnings		
Price indication	11500 USD (6000 USD)	incl mounting, cable, power supply, user interface
		6000 USD for "Zebra" which has lower specifications
Users (for lightning warnings)	mainly military	

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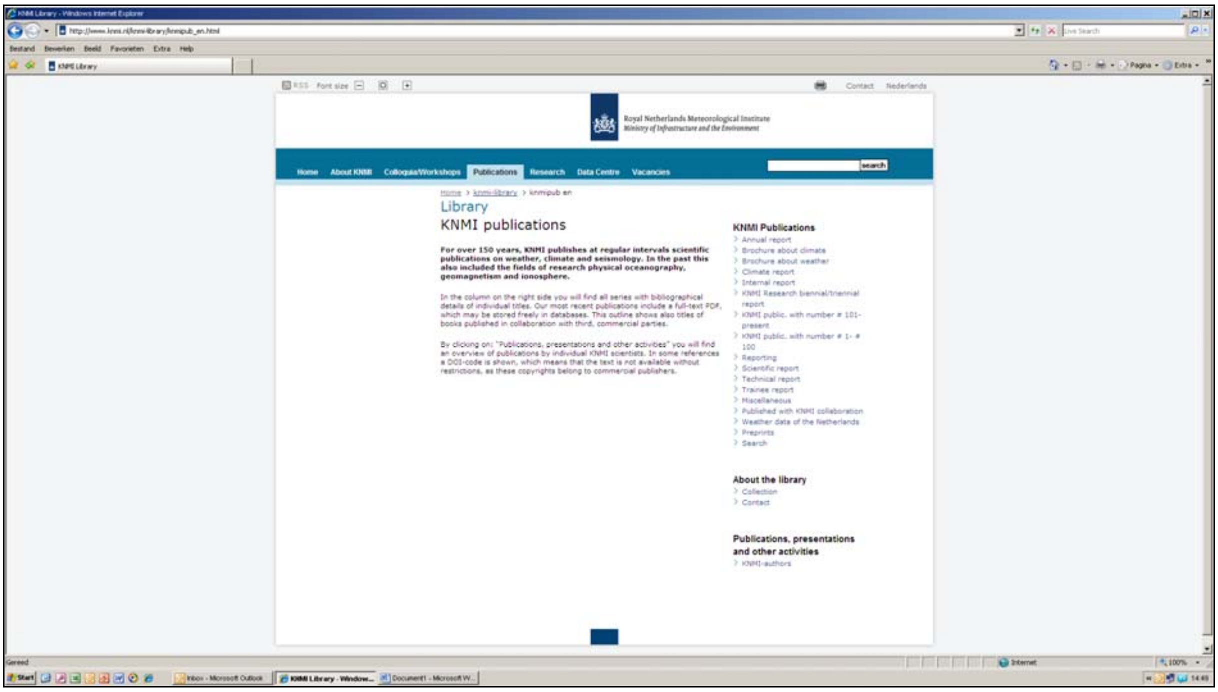

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