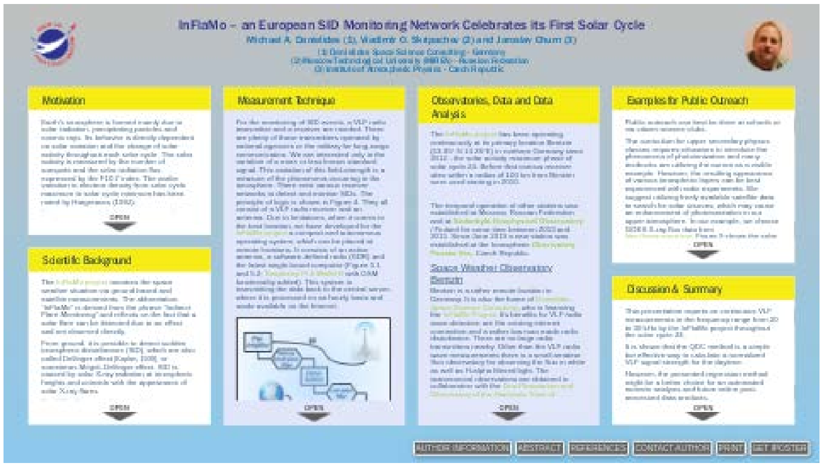
# InFlaMo – an European SID Monitoring Network Celebrates its First Solar Cycle




Michael A. Danielides (1), Vladimir O. Skripachev (2) and Jaroslav Chum (3)

(1) Danielides Space Science Consulting - Germany
(2) Moscow Technological University (MIREA) - Russian Federation
(3) Institute of Atmospheric Physics - Czech Republic

PRESENTED AT:

# MOTIVATION

Earth's ionosphere is formed mainly due to solar radiation, precipitating particles and cosmic rays. Its behavior is directly dependent on solar variation and the change of solar activity throughout each solar cycle. The solar activity is measured by the number of sunspots and the solar radiation flux expressed by the F10.7 index. The earlier variation in electron density from solar cycle maximum to solar cycle minimum has been noted by Hargreaves (1992).

Also, it is known that the ionospheric reflection height depends on, e.g. diurnal variations [Pal & Chakrabarti, 2010] and other sudden ionospheric disturbances. Its longer term variations are not well enough studied.

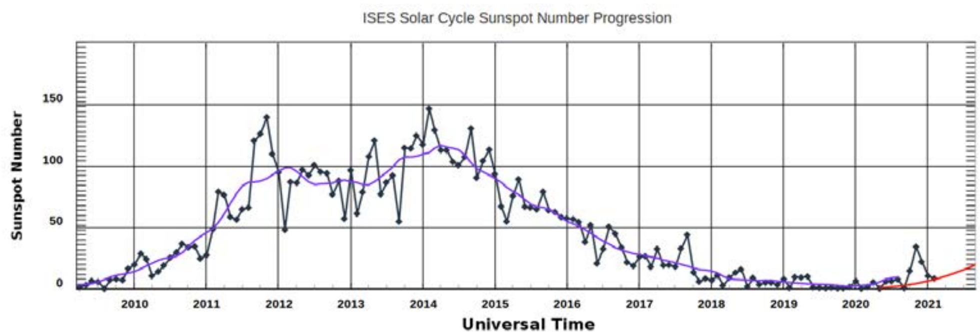



*Figure 1: Sunspot number versus time for the time period of the solar cycle 24, which started around 2009 and lasted until 2020. The red line on the right is an estimate. The blue line an average of the actual sunspot number measurements. Source: SWPC / NOAA (https://www.swpc.noaa.gov/products/solar-cycle-progression).*

Utilizing passive VLF ground based measurements with data coverage for almost the entire solar cycle 24, [Danielides & Chum, 2020] compared solar quiet absorption curves fitted by a cosine dependence. This cosine dependence includes fixed parameters based on geography and setup of the instrument. The variables are only the solar zenith angle and the D-region (http://www.inflamo.org/plugins/pictures/644877/current.png) absorption.

The aim of this iPoster is offering an insight to activities and possibilities the InFlaMo project (http://www.inflamo.org) may offer for students, citizen scientists as well as researchers.

# SCIENTIFIC BACKGROUND

The InFlaMo project (http://www.inflamo.org) monitors the space weather situation via ground based and satellite measurements. The abbreviation "InFlaMo" is derived from the phrase "Indirect Flare Monitoring" and reflects on the fact that a solar flare can be detected due to an effect and not observed directly.

From ground, it is possible to detect sudden ionospheric disturbances (SID), which are also called Dellinger effect [Kaplan, 1939], or sometimes Mögel–Dellinger effect. SID is caused by solar X-ray radiation at ionospheric heights and coincide with the appearance of solar X-ray flares.

The SID effect was discovered by John Howard Dellinger (https://en.wikipedia.org/wiki/John_Howard_Dellinger) around 1935 and also described by German physicist Hans Mögel (https://de.wikipedia.org/wiki/Hans_M%C3%B6gel) (1900-1944) in 1930. The fade-outs are characterized by sudden onset and a following recovery which can take from a few minutes to several hours. Those SIDs are modifying Earths very dynamic ionosphere especially at D- and E-layer heights.

Earth's upper atmosphere (Figure 2) allows only to view the Sun indirectly and the phenomena appearing on its surface. Being outside Earth's atmosphere provides a direct view onto the Sun. This is archived by using space probes and satellites. For the InFlaMo project (http://www.inflamo.org) the NOASs GOES solar X-ray satellite data (https://www.swpc.noaa.gov/products/goes-x-ray-flux#:~:text=The%20GOES%20X-ray%20plots%20shown%20here%20are%20used,%28CMEs%29%20which%20can%20ultimately%20lead%20to%20geomagnetic% is used as reference.

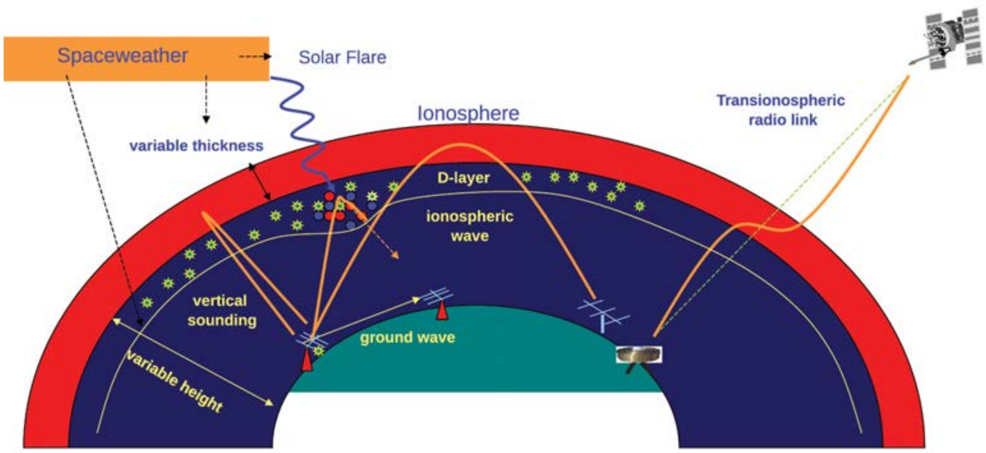



Figure 2) The figure shows a sketch of Earth's upper atmosphere, ground based instrumentation (radio transmitters, sounders and radio receivers), space instrumentation (satellites) as well as waves propagations. Earth's ionosphere is a variable system with a variable thickness and electron distribution (profile) depending on space weather events (solar activity, e.g. solar X-ray flares).

By comparing both direct (space based) and indirect (ground based) observations, a great deal of information can be provided. Especially, at times when availability of space based information is not guaranteed, due to active space weather conditions, which may limit the trans ionospheric radio link to research satellites, ground based observations are an only option. At the InFlaMo project (http://www.inflamo.org) this is considered as "*learning mother nature's language*".

When a solar flare occurs on the Sun (Figure 3), a blast of intense ultraviolet and X-ray radiation hits the day side of the Earth 8 minutes later.

Hard solar X-rays will penetrate down to the D-region, releasing electrons that will rapidly increase absorption, causing a High Frequency (3 - 30 MHz) radio blackout. During this time Very Low Frequency (3 – 30 kHz) signals are reflected by the D layer (http://www.inflamo.org/plugins/pictures/644877/current.png) instead of the E layer (http://www.inflamo.org/plugins/pictures/644877/current.png), where the increased atmospheric density is usually increasing the absorption of the wave and thus dampen it. As soon as the X-rays end, the SID or radio black-out ends as the electrons in the D-region recombine rapidly and signal strength return to normal.

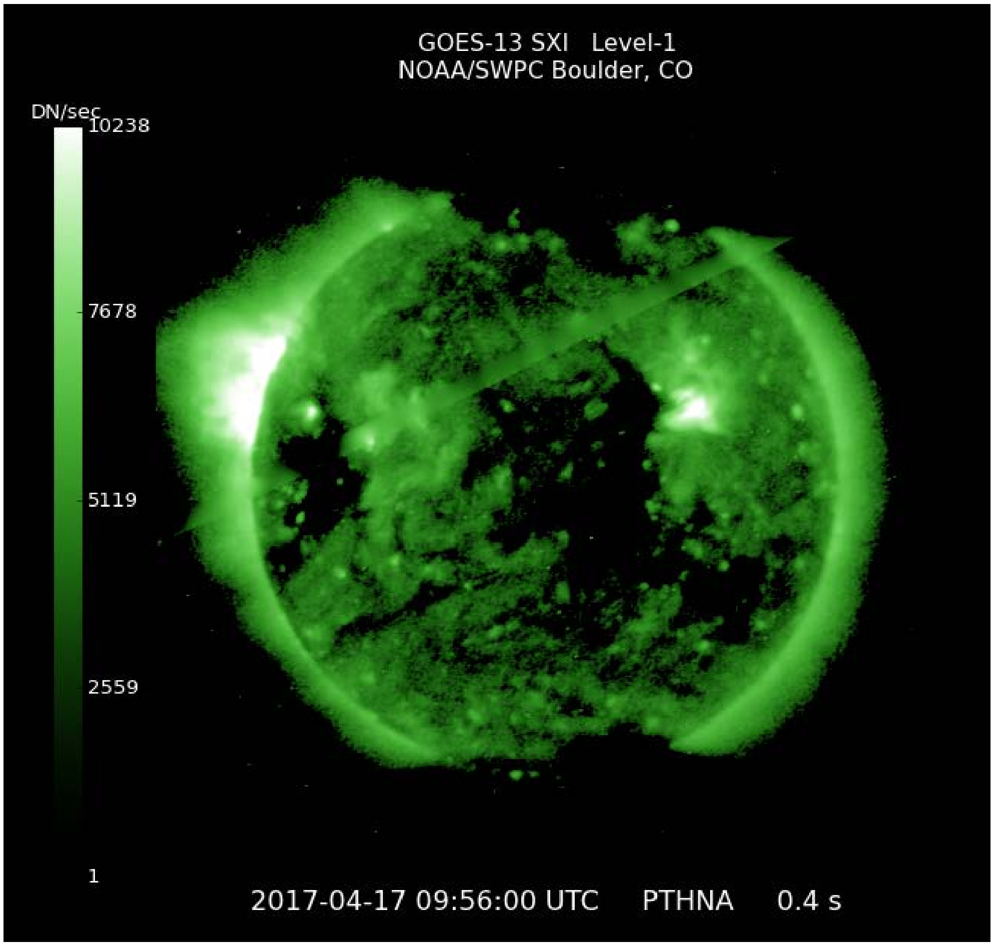



***Figure 3) The figure besides shows the Sun from the GOES 13 satellite on April 17th, 2017 at 09:56 UTC. A strong solar X-ray flare is visible in the upper left side of the Sun (credit NOAA / SWPC (https://www.swpc.noaa.gov/)).***

## MEASUREMENT TECHNIQUE

For the monitoring of SID events, a VLF radio transmitter and a receiver are needed. There are plenty of those transmitters operated by national agencies or the military for long-range communication. We are interested only in the variation of a more or less known standard signal. This variation of this field-strength is a measure of the phenomena occurring in the ionosphere. There exist various receiver networks to detect and monitor SIDs. The principle of logic is shown in Figure 4. They all consist of a VLF radio receiver and an antenna. Due to limitations, when it comes to the best location, we have developed for the lnFlaMo project (http://www.inflamo.org) a compact and autonomous operating system, which can be placed at remote locations. It consists of an active antenna, a software-defined radio (SDR) and the latest single-board computer (Figure 5.1 and 5.2; Raspberry Pi 4 Model B (https://www.raspberrypi.org/products/raspberry-pi-4-model-b/) with GSM functionality added). This system is transmitting the data back to the central server, where it is processed on an hourly basis and made available on the Internet.

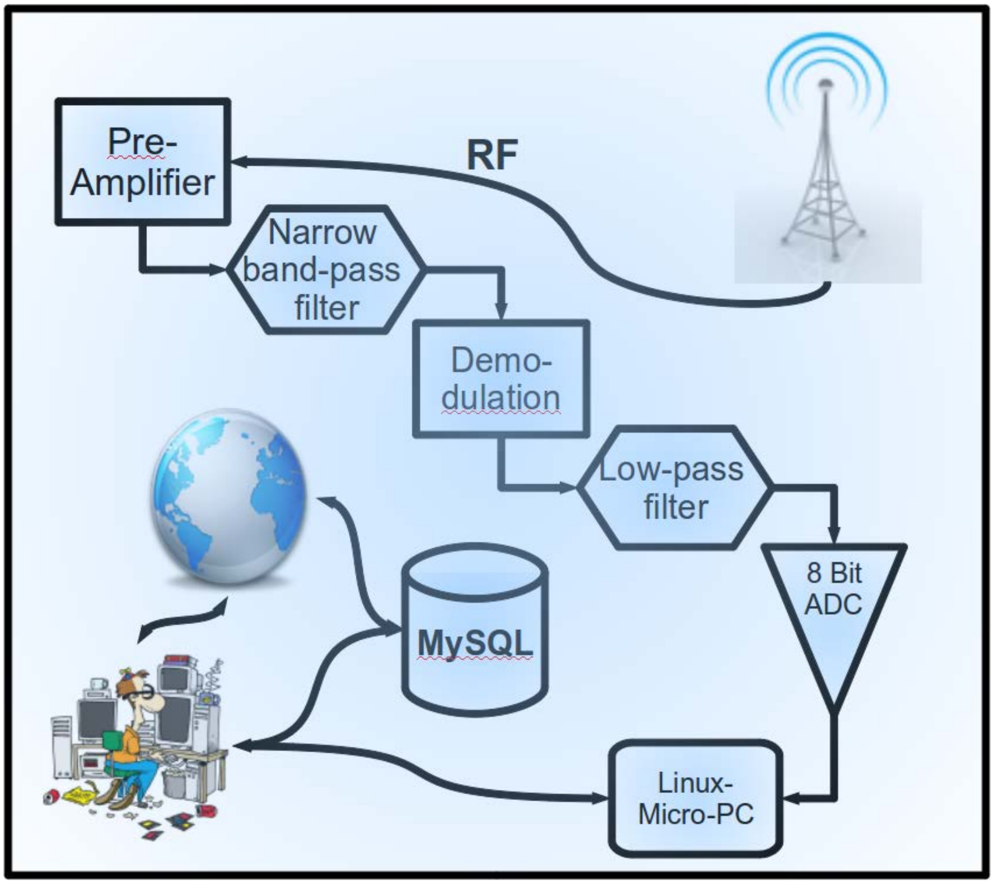



***Figure 4: Sketch of a single channel VLF receiver station logic. Today's InFlaMo SDR receiver stations (http://www.inflamo.org/technical-background.html) are broadband (multiple channel) receivers. With a SOR receiver several transmissions can be recorded simultaneously.***

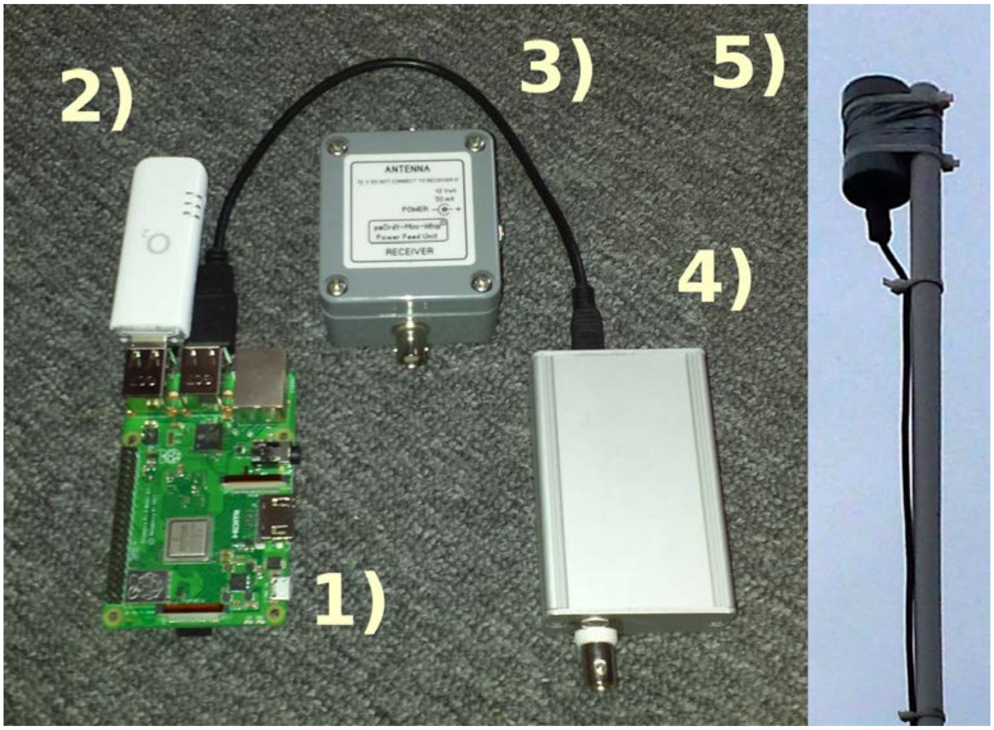



***Figure 5: The PAORT Mini Whip active antenna is an electric field active antenna in a small package (Figure 5.5.) This antenna type has been selected as the 'perfect' fit for our broadband VLF SID monitor (private Communication with Mr. Roelof Bakker). It is connected with a "Power Bridge" (Figure 5.3) to the SDR.***

An SDR is a broadband radio wave receiver where components that have typically been implemented in hardware (e.g. mixers, filters, amplifiers, modulators/demodulators, detectors, etc.) are instead implemented by means of software on a personal computer or embedded system. For the lnFlaMo project (http://www.inflamo.org), an amateur SDR (Figure 5.4) with a broad bandwidth from about 10 Hz to 60 MHz was chosen. Though it is only used for the frequency range between 10 and 50 kHz at a sampling rate of 1 second and average signal bandwidth of 50 Hz.

# OBSERVATORIES, DATA AND DATA ANALYSIS

The InFlaMo project (http://www.inflamo.org) has been operating continuously at its primary location Bentzin (53.95° N 13.28°E) in northern Germany since 2012 - the solar activity maximum phase of solar cycle 24. Before that various receiver sites within a radius of 100 km from Bentzin were used starting in 2010.

The temporal operation of other stations was established at Moscow, Russian Federation and at **Sodankylä Geophysical Observatory** (http://www.sgo.fi) / Finland for some time between 2013 and 2015. Since June 2019 a new station was established at the Ionospheric **Observatory Panska Ves** (http://www.ufa.cas.cz/en/institute-structure/department-of-ionosphere-and-aeronomy/panska-ves-observatory/), Czech Republic.

## Space Weather Observatory Bentzin

Bentzin is a rather remote location in Germany. It is also the home of Danielides Space Science Consulting (http://www.danielides.com), who is financing the InFlaMo Project (http://www.inflamo.org). It's benefits for VLF radio wave detection are the existing internet connection and a rather low man made radio disturbance. There are no large radio transmitters nearby. Other than the VLF radio wave measurements there is a small amateur Sun observatory for observing the Sun in white as well as H-alpha filtered light. The astronomical observations are obtained in collaboration with the Zeis-Planetarium and Observatory of the Hanseatic Town of Demmin (http://www.planetarium-demmin.de). The next ionosonde is located in a distance of about 100 km at Juhliusruh on the Island of Rügen. This ensures that one can obtain measured ionospheric density profiles for the region and has not only to rely on interpolated ionospheric model data.

The measured VLF data are available from http://src.danielides.eu/src/www.html (http://src.danielides.eu/src/www.html)They are hourly update.

## Panská Ves Observatory

The **Observatory of Panska Ves** (http://www.ufa.cas.cz/en/institute-structure/department-of-ionosphere-and-aeronomy/panska-ves-observatory/) (50.528°, 14.569°) is located in the Northern part of Czechia about 60 km from Prague. It belongs to the **Department of Ionosphere and Aeronomy** of the **Institute of Atmospheric Physics**, Czech Academy of Sciences. The observatory is used as a receiving station of satellites for magnetospheric and ionospheric research. E.g., **Magion** satellites were operated from here in the past. Currently, wideband instrument from CLUSTER mission (https://www.esa.int/Science_Exploration/Space_Science/Cluster_overview2) is received in Panska Ves. In addition, a number of ground-based ionospheric and atmospheric measurements are performed at Panska Ves. Namely, continuous Doppler sounding of the ionosphere, measurements of cosmic noise absorption (riometer in testing phase), airglow measurements of mesopause region (by DLR), measurements of atmospheric electricity, array of infrasound detectors, basic meteorological measurements and seismometer (Geophysical Institute).
Monitoring of VLF signals (receiver installed in the frame of InFlaMo project, Germany) represents a useful complementary information to the other ionospheric measurements (Doppler sounding and riometer) performed at Panska Ves. The InFlaMo receiver (http://www.inflamo.org/technical-background.html) mainly monitors changes in the lowest ionosphere (D layer (http://www.inflamo.org/plugins/pictures/644877/current.png)), e.g. changes due to variation of solar X-ray flux. On the other hand, Doppler sounding (Doppler shift) usually provides information about the fluctuations in the F layer (http://www.inflamo.org/plugins/pictures/644877/current.png). However, the amplitude of the Doppler signal also carries information about the attenuation in the D layer (http://www.inflamo.org/plugins/pictures/644877/current.png). The local changes of electron densities in the D layer (http://www.inflamo.org/plugins/pictures/644877/current.png) are also detected by riometer. Important information about the state of the ionosphere is also obtained from nearby vertical sounding by digital ionosonde. This multi-instrument observation provides useful information about the variation of the ionosphere from its bottom up to the maximum of ionization.

For this poster, data from the main location is used. In particular, the selected amplitude measurements of the relative field strength from the following VLF transmitter stations (call sign, country, frequency, latitude, and longitude) are analyzed:

- HWU, France, 20.90 kHz, 46.71° N, l.24°E
- GQD, Great Britain, 22.10 kHz, 54.73° N, 2.88°W
- DH038, Germany, 23.40 kHz, 53.07° N, 7.62°E
- NAA, USA, 24.00 kHz, 44.64° N, 67.28°W

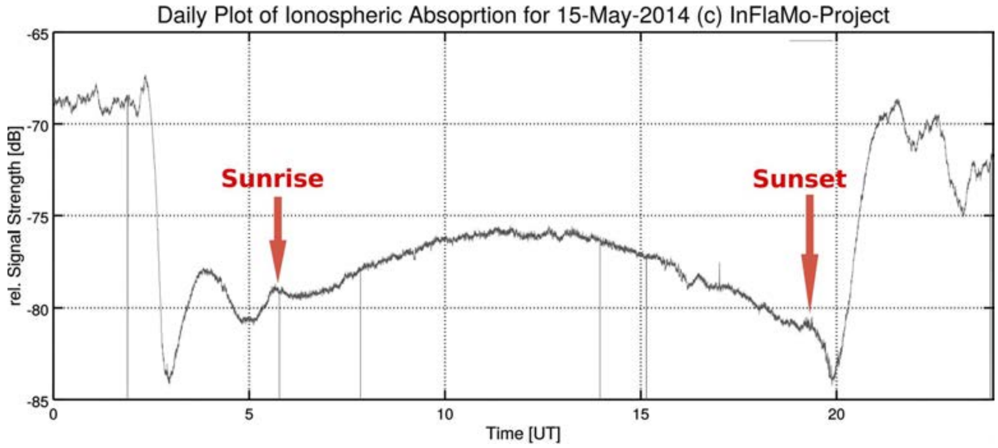



*Figure 6: Quiet day curve (QDC) from May 15th, 2014 at 22.1 kHz. Transmitted at Skelton, UK and recorded at Bentzin, Germany. The spikes in the data are caused artificially by sources nearby the receiver station. Times for sunrise at the transmitter station and sunset at the receiver station are marked*

An undisturbed measurement shows typical daily variations (Figure 6), which can be divided into day and nighttime conditions and the sunrise and sunset variations. Here we ignore the nighttime conditions and determine the sunrise and sunset times utilizing the algorithm for an approximate solar position [Michalsky, J., 1988]. Other researchers utilize the center of a great circle path between the transmitter and receiver station as a location to determine sunrise and sunset times. Here we simply take the sunrise time of the western station as well as the sunset time of the eastern station. Also, it does not matter which one is the transmitter and which one the receiver station. The day times are marked in figures in black. Times of enhanced noise level are mostly caused by thunderstorms on the path of the radio propagation. A sudden off level of a signal is a usual sign that the transmitter station has gone offline or maintenance was being performed (see Figure 7 graphs for NAA in the afternoon and for HWU during the entire day).

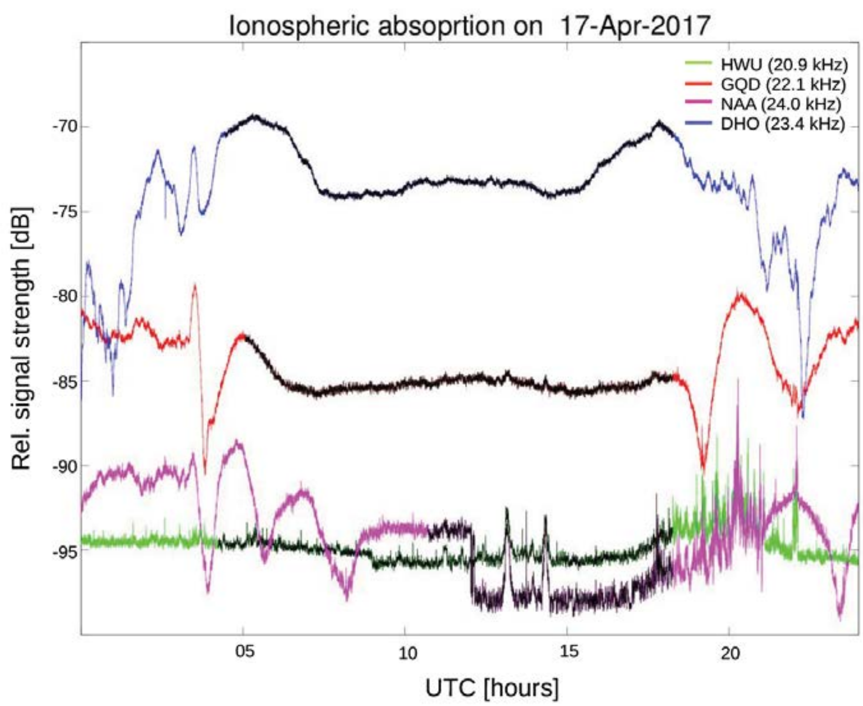



*Figure 7: Example of typical quiet daily measurements of 4 different VLF transmitters.*

## The regression method

The time interval which defines a quiet day curve is given by the time of the sunrise time of the more westward positioned station (transmitter or receiver) and the sunset time at the other station. Several regression methods are applicable for a fitting. Polynomial regression 2nd order provides an easy way to analyze the length of the sunlit condition as well as the relative maximum of signal strength at the mid-point (on a great circle) between the both transmitter and receiver stations. A Polynomial regression 8th order provides a most accurate fit for most quiet day curves, but includes too many fitting parameters. Therefore, the approach of a cosine regression from Schumer (2009) was applied for the present study. With the intensity of the signal, I(t), given

$$I(t) = A \cdot Cos^{0.9}(\Theta_t) + B \text{ (EQ. 1)},$$

where the parameter, A, is a scaling factor which contains information about ionizing Lyman-α flux, local NO+ densities, and background solar X-ray flux. The parameter, B, in equation 1 represents the received strength of the VLF signal in the absence of any loss. The power of that dependence, r =0.9, was found consistent with Schumer (2009) and references there-in, which suggested the power of the cosine dependence of D-layer (http://www.inflamo.org/plugins/pictures/644877/current.png) absorption at mid-latitudes is between 0.6 and 1.0. The zenith angle, Θt, is computed for the coordinate of the mid-point of the radio propagation path between transmitter and receiver.

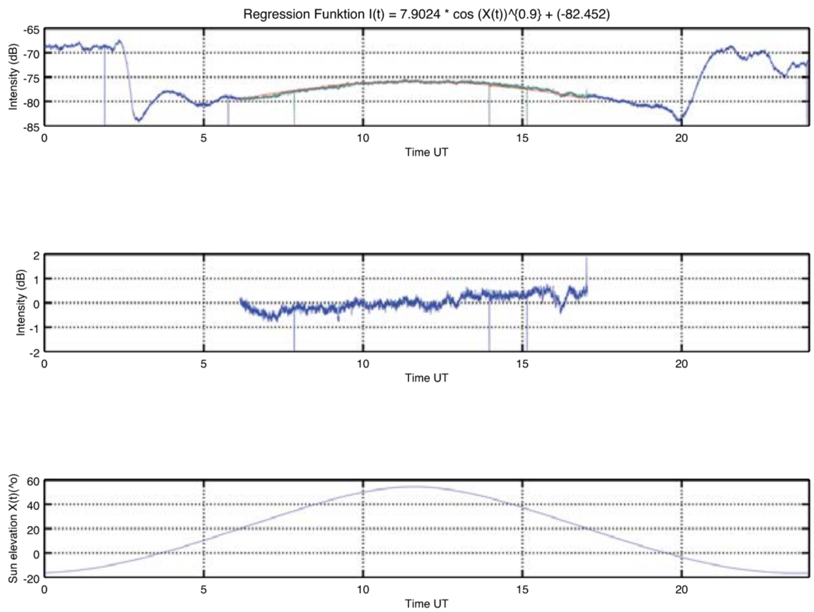



*Figure 8: Processing of a quiet data curve. Upper panel: The red line indicates the cosine regression. Middle panel: Resulting baseline of the subtraction of regression function from the data. Lower panel: Sun elevation vs. time.*

The upper panel of Figure 8 shows a typical quiet day curve. The cosine regression (EQ. 1) is computed for all the data points (green line), for which the solar elevation angle (Figure 8, lower panel) exceeds 20°. It was found that for solar elevation angles below 20° the change of ionospheric condition is too rapid to follow the cosine regression. The red line in Figure 8 (upper panel) is the actual regression curve plot onto the data. A good agreement can be seen. The middle panel is the resulting baseline of regression values subtracted from the data points. The parameters A and B from EQ. 1 are shown in the headline of the figure.

# EXAMPLES FOR PUBLIC OUTREACH

Public outreach can best be done at schools or via citizen science clubs.

The curriculum for upper secondary physics classes requires educators to introduce the phenomena of photoionization and many textbooks are utilizing the aurora as a visible example. However, the resulting appearance of various ionospheric layers can be best experienced with radio experiments. We suggest utilizing freely available satellite data to search for solar sources, which may cause an enhancement of photoionization in our upper atmosphere. In our example, we choose GOES X-ray flux data from http://www.nooa.gov (http://www.nooa.gov). Figure 9 shows the solar x-ray flux measured by the GOES 15 satellite on April 17th, 2017. It is not an undisturbed day. However, the ionospheric reaction will not appear as long as the solar x-ray flux is below a C class solar X-ray flare level. If the solar X-ray flux exceeds the value of an X class solar x-ray flare level, then the ionospheric reaction might behave non-linearly. Also, the C-class solar flare at 03 UTC is not of importance to our study since it is occurring at the station's local nighttime.

Citizen scientists as well as students at the described age group have got introduced to interpolation algorithms at their math classes. Many schools demand their students to utilize a computer algebra system (CAS) on their tablet-computers. The lnFlaMo measurements (http://src.danielides.eu/src/www.html) provide good data to exercise polynomial fits or subtraction of data points in order to find a normalized quiet day curve (QDC). Utilizing the QDC method is obviously the more reliable approach for our example. We see that a C2.5 solar flare corresponds here to about 1.6 arbitrary units in the plot (Figure 10). Curious observers might notice that the upper ionosphere shows no reaction as long as the X-ray flux is below 1E-6 W/m2 (C-class solar flare). In the case of an X-class solar flare, the ionosphere behavior is non-linear. Both regimes are marked yellow in the figures.

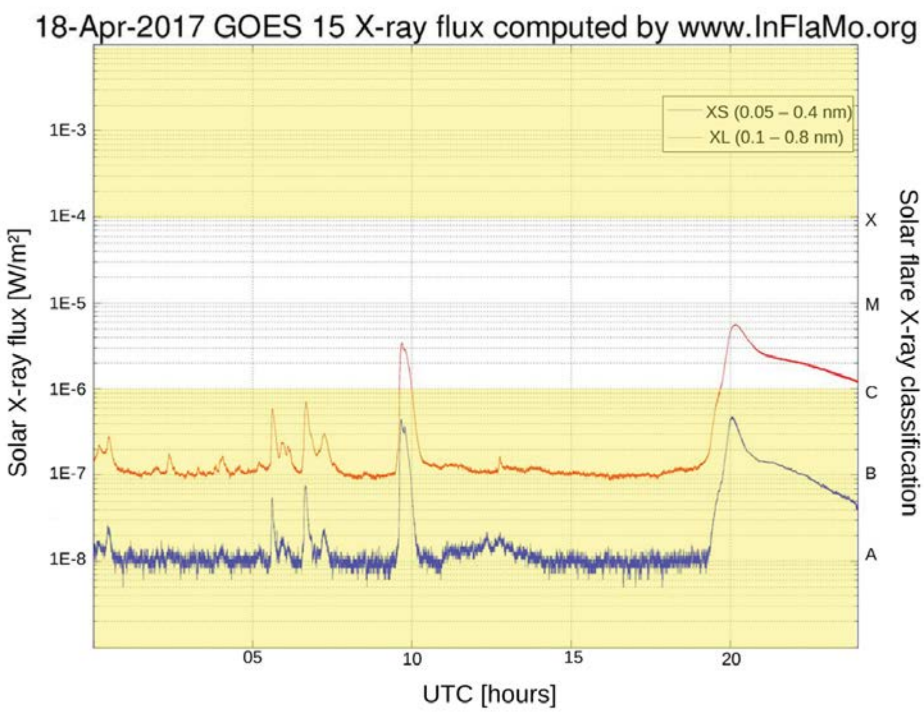


*Figure 9: C2.5 solar flare shortly before 10:00 UTC*

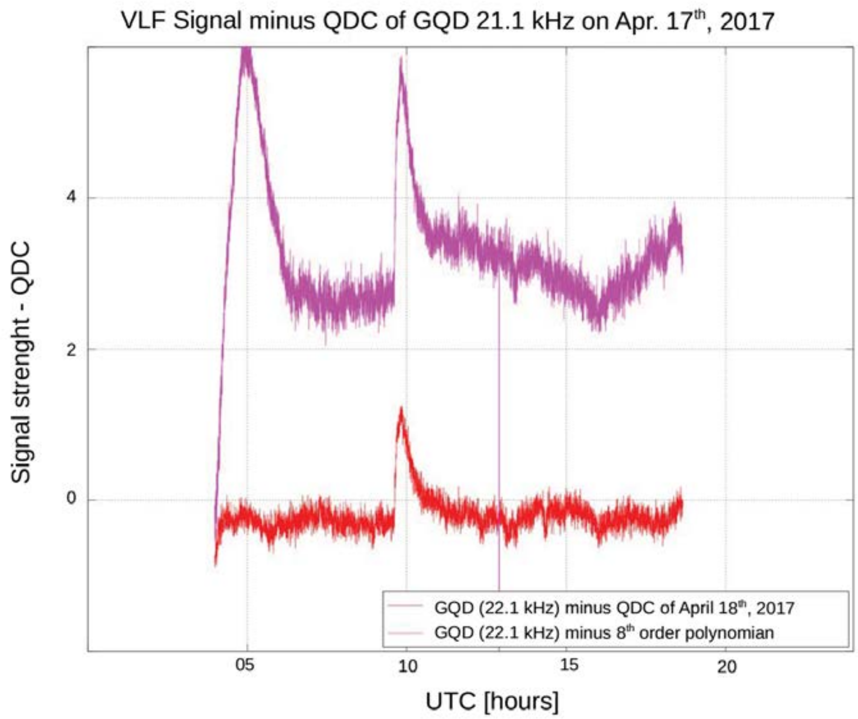



*Figure 10: The VLF daytime signals subtracted with I) a polynomial 8th order and ii) with a quiet day curve (QDC) from April 17th, 2017*

# DISCUSSION & SUMMARY

This presentation reports on continuous VLF measurements in the frequency range from 20 to 30 kHz by the InFlaMo project throughout the solar cycle 24.

It is shown that the QDC method is a simple but effective way to calculate a normalized VLF signal strength for the daytime.

However, the presented regression method might be a better choice for an automated numeric analysis and future online post-processed data products.

Other measuring techniques, such as riometer, ionosonde or attenuation of signals from Doppler sounders (Chum et al., 2018) can also provide valuable information about the D-region dynamics.

For solar cycle 24 this is not possible. The InFlaMo-Project (http://www.inflamo.org) has been operating a VLF receiver nearby the Doppler sounding radar since summer 2019.

For future studies the described cosine regression analysis combined with a multi instrumental setup will be used.

A solar X-ray flux can not be calculated from the corresponding SIDs and solar X-ray flares without further investigations on the radio propagation within Earth's atmosphere.

For that ion chemistry models and particle precipitation models need to be applied.

Finding a simplified power-law utilizing geomagnetic parameters for obtaining a good estimate for solar X-ray flux by ground based measurements might be a challenging goal. This is a matter for a further study.

The InFlaMo Project aims for a longitudinal global coverage. Collaboration with other VLF receiver sites in the Americas, Asia and Australia are welcome.

# AUTHOR INFORMATION

(1) Danielides Space Science Consulting (DSSC), Germany, (michael@danielides.com),

More information about Dr. Michael A. Danielides are found at http://www.danielides.com/experience.html (http://www.danielides.com/experience.html)

Researching VLF-radio wave propagations requires reaching out for high places. Here Dr. Danielides is installing the mini-whip active antenna on top of one of the measurement containers at Panska Ves Observatory, Czech Republic.

(2) MIREA – Russian Technological University, Russian Federation (skripatchevv@gmail.com)

(3) Institute of Atmospheric Physics, Czech Academy of Sciences, Czech Republic (jachu@ufa.cas.cz)

# ABSTRACT


## InFlaMo – an European SID Monitoring Network Celebrates its First Solar Cycle

The influence of solar X-ray radiation on terrestrial radio communication was found in the early 20ies century. But it was not understood immediately. Radio communication was a challenging topic back then, and became quickly a topic taught in science classes at school. Half a century later – with the start of the space age - it became evident, that the study of Earth's upper atmosphere was solving this question. Solar and other cosmic radiation is responsible for the condition of the ionosphere and the cause of black-outs in long range radio communication. Today, most of the ionospheric very long frequency (VLF) radio propagation phenomena are known and presumably almost completely understood, though it stays a challenging topic listening to the ionospheric disturbances caused by our Sun. The recent development of low-cost software defined radio wave receivers (SDRs) are an ongoing process and opens many new opportunities for applications in people's daily lives and in education. Furthermore, monitoring of Earth's lower ionosphere by utilizing VLF monitors, which are based on SDR technology, it offers new indirect insights into what happens on the Sun. Therefore, one aim of this presentation is to reach out to an educator community as well as citizen scientists to make the InFlaMo (Indirect solar Flare Monitoring) project (http://www.inflamo.org (http://www.inflamo.org)) better known. For almost the entire solar cycle 24 VLF data (20 to 30 kHz) was collected and preprocessed. The scientific analysis of the VLF data is an ongoing activity. For scientific and educational use InFlaMo project data is shared with researchers, educators and citizen scientists. The other aim is to enlarge the network of ground based multichannel SDR-receivers from Europe to overseas. The European network stations have been or are presently in Germany, Finland, Russian Federation and Czech Republic. With this rather inexpensive method monitoring the state of the ionosphere and recording the appearance of solar X-ray flares can be made available for class-room usage.

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