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Protection against lightning at a geomagnetic observatory

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Abstract. The Sinji Vrh Geomagnetic Observatory was built on the brow of Gora, the mountain above Ajdovščina, which is a part of Trnovo plateau, and all over Europe one can hardly find an area which is more often struck by lightning than this southwestern part of Slovenia. When the humid air masses of a storm front hit the edge of Gora, they rise up more than 1000 m in a very short time, and this causes an additional electrical charge of stormy clouds.

The reliability of operations performed in every section of the observatory could be increased by understanding the formation of lightning in a thunderstorm cloud and the application of already-proven methods of protection against a stroke of lightning and against its secondary effects. To reach this goal the following groups of experts have to cooperate: experts in the field of protection against lightning, constructors and manufacturers of equipment and observatory managers.

1 Formation of lightning

The ionized air in the bottom layers of the atmosphere occurs because of the thermodynamic circulation of the air containing specific percentages of humidity, solid particles and ions (Handbook of Geophysics and Space Environment, 1985; Čop et al., 2013). Electrical charges inside a thunderhead start to separate as early as at the beginning of the thunderhead formation. There are different theories about the spatial distribution of charges inside a thunderhead. Observations show that most of the positive charges are in the upper region of clouds, several kilometers from the negatively charged region. For this reason the most likely is a theory which assumes that opposing charges within the cloud occur due to collisions between the solid particles within the thunderhead. The electric field inside a cloud, which rarely exceeds 100 V cm^{-1}, is a result of opposing charges within the cloud (Ziegler et al., 1991; Saunders, 2008). The point discharge streamers arise by intensification of the electric field, and they occur if the strength of the electric field is greater than 4 kV cm^{-1}.

The critical value of the electric field strength in the air mixed with water drops is approximately 10 kV cm^{-1}. Above this critical value the air becomes conductive or, in other words, the process of ionization starts. An intensifying electric field in the cloud forms the first stepped leader stroke which progresses through the channel of ionized air. Due to the excessive negative charge the leader moves towards the opposing charge. It can move in steps of 5 to 50 m and is not the actual lightning stroke; it is a stepped leader. It can branch out and form more parallel channels with very high ohm resistance and consequently a small electric current of approximately 20 mA. Near the ground the positive streamers reach upwards towards the negative leader. The positive streamers lengthen as the negative stepped leader moves towards the ground. The return stroke occurs when an ionized path between the cloud and the earth is completed – that is, when the leader stroke approaches one step or more above the ground, a positive streamer shoots upwards from a prominent object and meets the negative leader.

Approximately 80 % of all lightning strokes have two or more return strokes. The average initial negative lightning stroke has an electric current of 30 kA, while overall negative-charge lighting has an electric current of 120 kA and positive-charge lightning has a current of 300 kA. A lightning stroke has the electrical power of 10^{12} W and lasts an average of 30 ms. According to the place of occurrence the most common types of lightnings are intracloud and only 10 % of all flashes are cloud-to-ground lightnings.

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The polarity of cloud-to-ground lightning is defined by a polarity of charge which will be neutralized after the electrical discharge. As the bottom region of a cloud is usually the center of a negative charge, more than 90 % of all lightning flashes are negative. As a rule positive lightning flashes have high amplitudes and frequently occur before the decay of a cloud. During the summer most flashes are negative and during the winter half of all the flashes are positive. However, the number of lightning flashes during the winter time is rather low, so the contribution of the positive lightning flashes to the results of overall statistical analysis may be deemed negligible.

According to their direction, cloud-to-ground lightning flashes are divided into updraft and downdraft. The most common is downdraft lightning. Updraft lightning usually occurs where an electrical field is strengthened by the geometry of the structures located on the ground: TV towers, steeples, high and sharp spires, skyscrapers and trees.

The enormous surge of a current through the ground surrounding the structure directly hit by a lightning stroke is dangerous, causing damage to electric power devices and installations, and injuries to users and all other living beings standing on the ground in the vicinity of the stroke, which can even electrocute them. A lightning stroke can also cause fire due to the high temperatures (25 000 K) in the lightning channel of ionized air. The electromagnetic waves which occur during the electrical discharge from a cloud into the surrounding air may induce high voltages in the electric power cables and signal cables.

Each starting electrical discharge of a thunderstorm cloud also induces an electrical charge in the structures and on the ground under this thunderstorm cloud. The induced electrical charge will remain as long as the cloud stays in the vicinity and until the cloud charge releases in the form of a lightning stroke. At that moment the induced electrical charge is no longer tied to the cloud, and it starts to propagate through the ground radially outwards from the lightning stroke point in the form of a voltage surge and with a speed close to the speed of light: $u = q/C$ [$\mathrm{As\,F^{-1} = V}$]. This surge of voltage through the ground is called an indirect lightning stroke, and it causes damage to living beings and structures near a point which is directly hit by a lightning stroke. The voltage in the ground decreases in inverse proportion to the distance from the point hit by a lightning stroke (Punekar and Kandasamy, 2011; West, 2011).

2 Slovenian Centre for Automatic Localization of Air Discharges

The Slovenian Centre for Automatic Localization of Air Discharges, hereinafter referred to as the SCALAR, was established in 1998, with the task of locating lightning stroke points between the cloud and the ground, and communicating the data to the final users.

Table 1. Data on lightning strokes in Slovenia.

Region	Max amplitude [kA]	Median amplitude [kA]	$p = 98\,\%$ [kA]
Slovenia	416.28	10.82	58
Primorska	385.73	11.15	60
Central part	416.28	11.09	60

SCALAR calculates the location of each lightning stroke on the basis of data recorded by sensors which monitor both components of the electromagnetic field or just its electrical component. Their sensors, which are a part of the network European Cooperation for Lightning Detection (EUCLID), transfer the detected data to Vienna, where, within the framework of EUCLID, the location of each lightning stroke and all the relevant data about it are calculated. More than 147 active sensors, covering the area from Sicily to Nordkapp, are currently included in this European network.

The following data are stored on the servers of SCALAR:

- strike time
- latitude and longitude of a lightning stroke point
- lightning current amplitude in kiloampere and the number of return strokes
- semi-axes and slope of an error ellipse
- accuracy of the calculated parameters of the recorded lightning stroke.

The statistical data on the lightning strokes in Slovenia, stored in SCALAR during the past 15 years, are collected in Table 1 (SCALAR, 2012). The map of maximum density of lightning strokes in Slovenia is drafted on the basis of the SCALAR data (Map of Maximum Values of Density of Lightning, 2007).

The mountain Gora is situated in the Slovenian region with a high density of lightning strokes, with a maximum yearly density of 7.8 lightning strokes $\mathrm{km^{-2}}$, as shown in Fig. 1. The density of lightning strokes in Slovenia is from 0.6–1.1 lightning strokes $\mathrm{km^{-2}\,year^{-1}}$ in the Prekmurje region, through 2.5–3.7 lightning strokes $\mathrm{km^{-2}\,year^{-1}}$ in the Ljubljana town depression, to as high as 6.3 lightning strokes $\mathrm{km^{-2}\,year^{-1}}$ and even more on the Trnovo plateau. The western part of Slovenia is particularly exposed to lightning strokes, and according to the relevant recorded data their frequency is the highest in Europe.

3 Thunderstorm at the observatory

The report no. 30/1/8/2012 on lightning strokes for the period from 12 September 2012 at 00:00:00 LT to

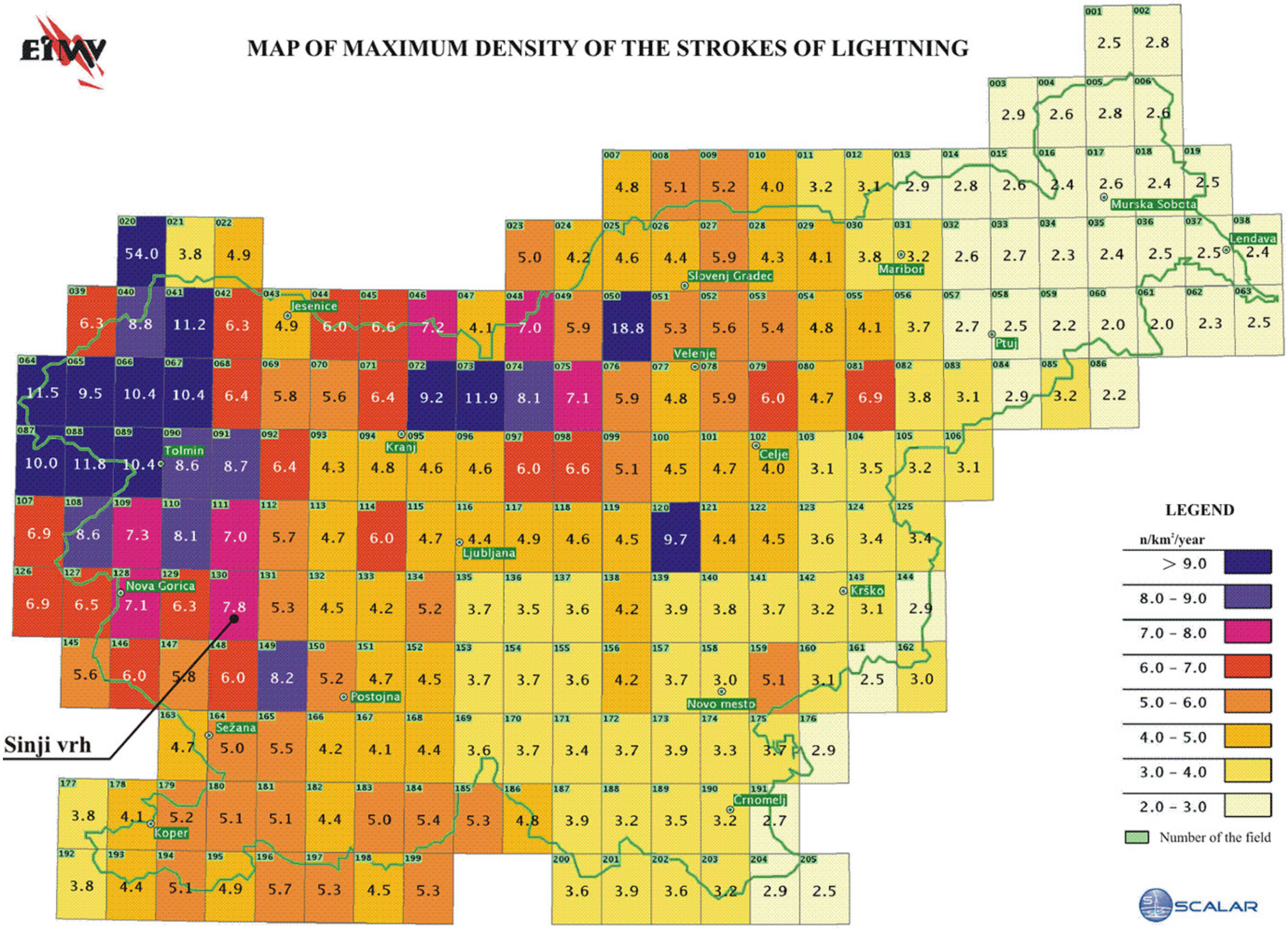

Figure 1. Map of the maximum yearly number of lightning strokes per km^2 in Slovenian territory.

14 September 2012 at 23:59:59 LT was drafted on the basis of the measurements carried out by SCALAR. The report describes 15 lightning strokes at the location of 4.5 km around the observatory. Table 2 with the data of lightning strokes was first supplemented with the results of calculations for distance L between the lightning stroke points Y, X and the observatory.

The thunderstorm on 12 September 2012 damaged the electronics of a three-axis fluxgate magnetometer, hereinafter the variometer (Lanza and Meloni, 2006). The magnetogram of variations of components of the geomagnetic field before the formation of the thunderstorm shows the typical double oscillation at 10:30 and at 12:00 LT. Such oscillations were observed every time upon the arrival of thunderstorm fronts from the southwest. In this case also the change in the geomagnetic field during a day and night was less distinctive than during a magnetically calm and sunny day. The variometer registered the first lightning stroke on 12 September 2012 at 12:47:25 LT and stopped registering at 13:55:02 LT as shown in Fig. 2. At that time some electronic parts were burned out, including the output parts of high-frequency excitation and compensation with the direct current (DC) and operational amplifiers at all three input stages. The start of interruption of registration was fitted with the SCALAR measurements, presented in Table 2. However, during the thunderstorm the variometer also registered electrical discharges which were not from hitting the ground but from discharging intra-cloud or cloud to cloud.

The lightning stroke which during the thunderstorm on 12 September 2012 destroyed the electronic parts of the variometer was the ninth in a row, and was 1km from the observatory, as can be seen in Table 2. The positive particles that carry an electric current of 106.264 kA reached 27.55 % of the strongest lightning strokes ever registered thus far in the Primorska region, presented in Table 1. The secondary influence of this lightning stroke exceeded the upper voltage limit for which the instrument was designed. This overvoltage occurred due to the electromagnetic influence of the lightning current pulses on the coils in the sensors of instruments. On the basis of this assumption the value of the induced voltage in each coil of the variometer sensor is given by Eq. (1):

Table 2. Data on lightning strokes during the thunderstorm on Gora.

N_x	Date	Time [LT]	Y	X	Amplitude I [kA]	Distance L_x [km]	Ratio N_x/N_9
1	12 Sep 2012	12:47:25.4	5414100	5083344	−18.796	3.695	−0.05
2	12 Sep 2012	12:47:25.5	5414257	5083345	−19.203	4.043	−0.05
3	12 Sep 2012	12:47:25.5	5413911	5083661	−10.342	3.673	−0.03
4	12 Sep 2012	12:47:25.6	5413844	5083382	−98.975	3.837	−0.27
5	12 Sep 2012	12:47:25.9	5414250	5083286	−17.409	3.804	−0.05
6	12 Sep 2012	12:47:26.0	5414254	5083337	−18.371	3.634	−0.05
7	12 Sep 2012	12:47:26.9	5414192	5083464	−9.990	3.634	−0.03
8	12 Sep 2012	13:05:28.3	5416274	5083469	6.827	1.778	0.04
9	12 Sep 2012	13:55:07.4	5417713	5083341	106.264	1.111	1.00
10	12 Sep 2012	20:57:14.5	5419086	5082530	−4.052	2.319	−0.02
11	12 Sep 2012	21:18:11.7	5417455	5081774	9.102	2.753	0.03
12	12 Sep 2012	21:31:03.4	5420204	5085123	−10.619	2.341	−0.05
13	12 Sep 2012	21:31:03.5	5419871	5085407	−15.170	2.160	−0.07
14	12 Sep 2012	21:57:00.5	5422317	5083773	7.678	4.349	0.02
15	12 Sep 2012	21:57:00.6	5420535	5081331	178.081	3.915	0.48

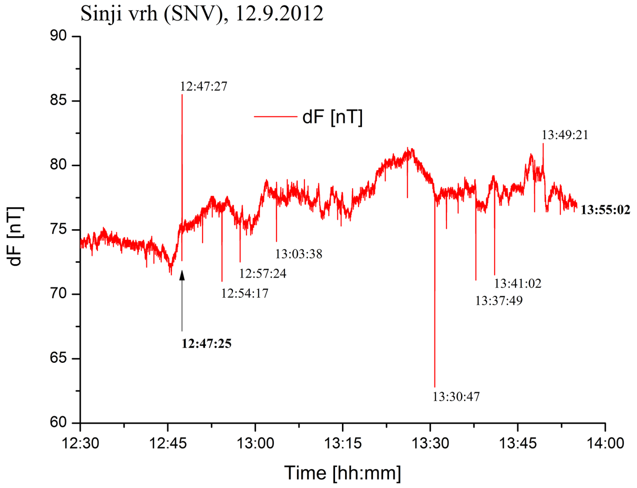

Figure 2. Variations in the geomagnetic field's absolute values during the thunderstorm on Gora.

$$u_{\mathrm{i}} = -N\,\frac{\mathrm{d}\Phi}{\mathrm{d}t} = -N\,\frac{\mathrm{d}\,(S\,\mu_0\,H)}{\mathrm{d}t} = -k\,L_x\,\frac{\mathrm{d}I}{\mathrm{d}t}. \qquad (1)$$

The induced voltage u_{i} is reciprocally dependent on the distance L_x between the lightning stroke point and the observatory. If the time variation of the lightning currents $\mathrm{d}I/\mathrm{d}t$ is approximately equal, one can calculate the influence of each separate lightning stroke on a measuring instrument N_{x}/N_9, presented in Table 2. This assessment was given relating to the lightning stroke N_9 which destroyed the electronics of the variometer. It can be used for the assessment of effectiveness of the built-in additional protection against lightning stroke effects.

4 Protection against lightning stroke effects

The first lightning strokes on the location where the observatory is situated were recorded in the summer of 2009, during the test measurements of changes in the geomagnetic field. These records were used for designing the appropriate electricity supply system of the observatory. For the final decision on the location of the measuring posts and temporary facilities of the observatory, we had to comply with the regulatory provisions relating to setting the posts in nature and to obey the conditions prescribed by the Slovenian Environmental Protection Agency. In addition, we had to assure greater reliability of the observatory operations and to reduce the effects of lightning strokes (Rupke, 2002; Protection Against Lightning Effects, 2009). The first construction phase was carried out in three stages. For the reason of safety each stage is equipped with its independent DC supply system of 12 V. When the first phase was completed and after the measuring instruments were connected, a comparison of the measurement results with those at the surrounding geomagnetic observatories was made (Čop et al., 2011).

Protection against overvoltage of atmospheric origin at the observatory was built up gradually, as there were no issued recommendations regarding the protection against lightning stroke effects which would specifically address protection at geomagnetic observatories (Wienert, 1970; Jankowski and Sucksdorff, 1996). The classical system of overvoltage protection leans on the protection ground. In the separate structures standard elements for overvoltage protection are mounted in the main distributing box of electrical energy. They are connected to the protection ground with wires for protection which lead away the surplus electric charge. For more sensitive consumers the standard protection elements

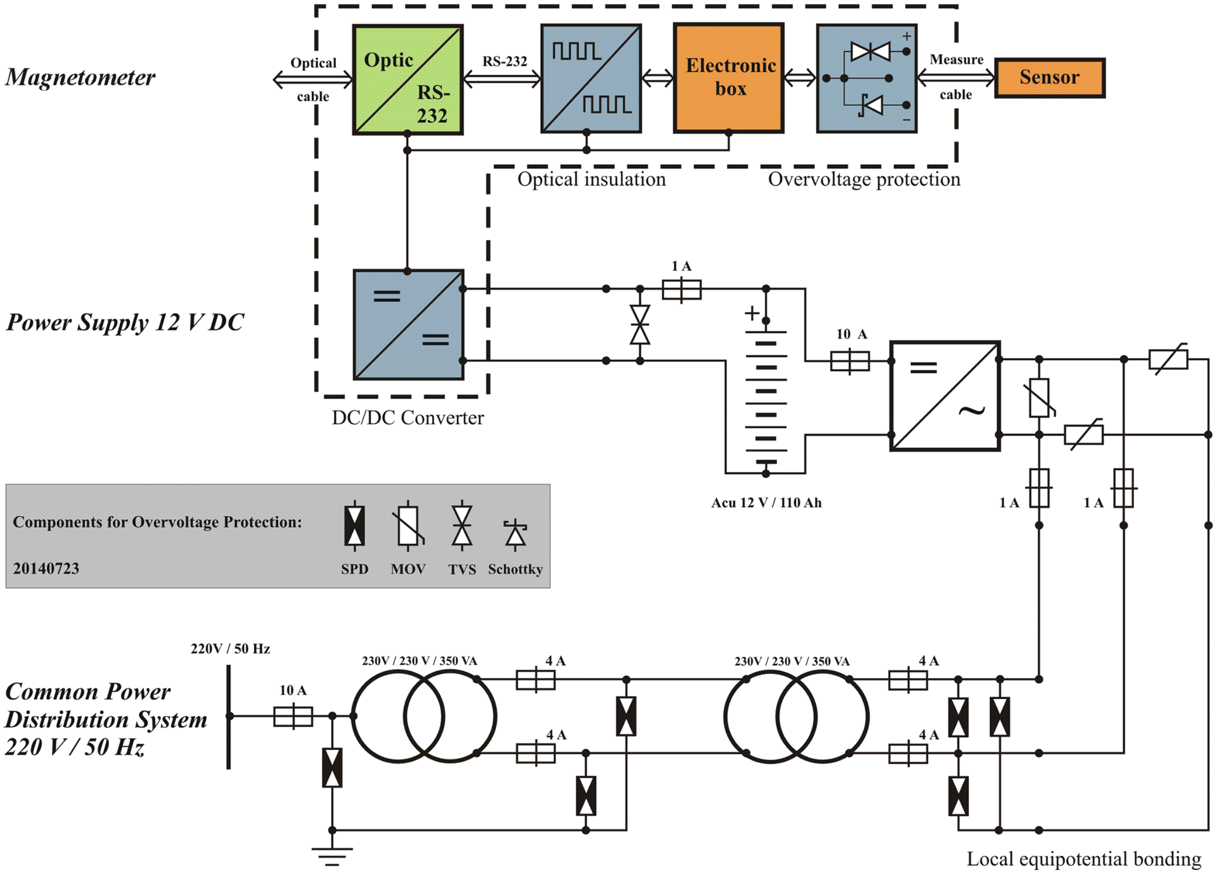

Figure 3. Flow diagram of the connection of the variometer on the low-voltage power supply network and its protection against overvoltage.

are mounted near to them. In these cases the protection connections are used for equilibration of potentials.

As early as during the planning process for the construction of the observatory, consideration was given to obtaining the complete protection of the observatory against overvoltage through the low-voltage overhead lines in the public distribution network. Connection of the observatory to the public distribution network was carried out through two separation transformers connected in a series and via standard surge protection devices (SPDs) for the protection of consumers. These standard devices were integrated into the distribution units of electric power of 220 V, 50 Hz, as shown in Fig. 3. The observatory is on the Trnovo highland plateau (Karst area), 867 m a.s.l. (above sea level). At the distance of 2.8 km this plateau rises up from the valley of around 100 m a.s.l. During the dry periods the same 100 m thick limestone of Gora becomes an excellent insulator and the ground wire becomes an antenna for lightning strokes. For this reason the source of electrical energy for the variometers is totally insulated by the cascade of two transformers. Each of them functions like a limiter which, in serial connection, composes a robust electric filter and offers reliable overvoltage protection.

We made an effort to reach the optimal solution for two opposing requirements relating to the location(s) of the measuring instruments and other electronic devices: the first requirement regarding the accuracy of measurements tends to keep the distance between instruments/devices as long as possible to avoid the influence of one instrument/device on another; the second requirement regarding the decrease of lightning stroke effects is the tendency to make electrical circuits as short as possible. The measuring data have therefore been transferred through optical fibers instead of long copper wires.

The protection of the observatory against lightning stroke effects that may reach the observatory through the low-voltage overhead lines in the distribution network with two transformers in cascade has proven to be very effective. The purchased communication converters were selected to comply with three requirements: (a) to be available for purchase, (b) to be industrially constructed and (c) to operate without malfunctions. The integrated parts of telemetry, analog-to-digital converters and battery chargers were selected in accordance with the same requirements as the said communication converters. The chargers are used for charging the stationary batteries which provide the observatory with electricity supply autonomy for at least a week.

Among all parts of the measuring systems at the observatory, due to the secondary effects of a stroke of lightning, only the electronic parts of the variometers were destroyed in 2012 three times in a row. The analog parts were affected twice and the digital parts were affected once. Thereupon the distribution units of the electric power supply of 12 V DC were additionally protected against overvoltage through the additionally installed transient voltage suppressor (TVS) diodes (Protection by TRANSIL, 2004) together with standard 1A fuses. The DC supply of all magnetometers has additionally been galvanically separated from their electronic parts by DC-to-DC converters, so that the lengths of incoming wires do not exceed 0.5 m. The length of signal cables RS-232 has also been shortened by optical interfaces.

For the protection of analog electronics of the variometers against overvoltage of atmospheric origin, we decided to install fast-acting diodes in all wirings between their sensors and analog electronics (Transient Overvoltage Protection, 2008). These diodes were envisaged to be located between the wiring connections and supply cables. We were able to connect the fast-acting diodes in the measuring system of these variometers, which have a virtual zero, only after we had contacted their manufacturer for help. We installed the diodes as a bridge between each input of operational amplifiers for each channel separately, outputs for high-frequency excitation and outputs for compensation with DC as follows: TVS diodes to supply voltage of $+15$ V and Schottky diodes to supply voltage of 0 V. This overvoltage protection of wiring was installed between the electronic parts and the incoming sensor cables. As the nonlinear elements of the protection were connected in parallel with the coils of the sensors, it was necessary to define once again the measuring coefficients between the analog values of voltage of each component of the geomagnetic field in millivolts and their values of the magnetic field density in nanoteslas. The first variometer with described overvoltage protection was put into operation before 15 January 2013, when a huge snowstorm with lightning at the observatory occurred (Čop and Deželjin, 2014).

In 2013 two of three battery chargers were destroyed because of an instance of atmospheric overvoltage but no variometer. It will therefore be necessary to add a third protection against lightning strokes. The power supply cables of 220 V, 50 Hz behind the separation transformer are envisaged to be additionally shortened, so that their length will not exceed 5.0 m. Our intention is to reach this goal with an additional fast-acting overvoltage protection metal oxide varistor (MOV), which is usually used for the protection of lesser consumers of 220 V, 50 Hz, such as TV sets, computers and telephone sets. This overvoltage protection should be located as near to a consumer as possible. The consumer's metal housing determines the local grounding point, which is connected with a copper wire, no longer than 0.5 m, with the protection components. The important thing is to provide the potential equalization through the common ground conductor (Transient Voltage and Lightning Protection Systems, 2010).

5 Conclusions

The existing atmospheric overvoltage protection of the variometers at the observatory successfully endured all the storm periods during 2013. So far in this period, in the vicinity of the observatory, none of the lightning strokes that have occurred were as strong as the one with maximum amplitude registered in Slovenia, as shown in Table 1. It is possible to obtain a reliable statistical data set only through a long-term research project, funded by a suitable source.

For the purpose of safety we still use the reserve electronics of a variometer without overvoltage protection only during the absolute measurements with a theodolite DI (Declination Inclination) magnetometer. For the continuous recording of the components of the geomagnetic field, we have used a basic electronic box of the variometer which is equipped with additional overvoltage protection.

The observatory operates without a regular crew, and it uses telemetry for transmission and reception of measuring data. Therefore it is at risk not only because of lightning strokes but also because of vandalism and forest fires. To solve these problems we spent a lot of time during 2013 searching for an appropriate reserve location for backup measurements. If we were to install at least one variometer on the reserve location, we would significantly reduce the possibility of interruption of regular measurements at the observatory. We could even avoid the difficulties if all the equipment at the observatory were destroyed. The winter weather conditions on Gora temporarily prevent us from working on preparation of the reserve location in the vicinity of the observatory, but we shall be able to continue this work in the spring of 2014.

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