BUILDING RESILIENCE AGAINST SPACE WEATHER EFFECTS

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Abstract: *Modern technology and socio-economic systems have become increasingly vulnerable to the effects of space weather, geomagnetic and ionospheric disturbances, that undermine the benefits to society. The causes of disruptions lie in vulnerable technologies (such as satellite navigation, power distribution and radio communications) that establish the national infrastructure. Here a resilience scheme for vulnerable technologies in national infrastructure is proposed, that comprise risk assessment, space weather monitoring and forecasting, and corrective actions during the scenarios of intense space weather and ionospheric disturbances, aimed at sustainable and robust operation of both the fundamental technologies and the technology and socio-economic systems and services relying on the national infrastructure.*

KEY WORDS

1. RISK 2. SPACE WEATHER 3. IONOSPHERE 4. RESILIENCE

1 INTRODUCTION. Space weather causes considerable effects on numerous technology and socio-economic systems comprising the national infrastructure. While it affects both the economic activities and everyday life of the individuals, a proper approach to building resilience against space weather effects is still at its infancy.
Here we address the problem and propose the solution in the form of implementation of the Technology Resilience Scheme (TRS) against space weather effects, thus allowing for establishing robustness against potential risks and threats of deteriorations, temporal suspensions or even cessation of services based on space weather-prone technology systems. Practical deployment of TRS is presented through the activities of the GNSS Space Weather Laboratory at Faculty of Maritime Studies, University of Rijeka, Croatia.
Finally, the future developments in rising the general awareness of the space weather effects are addressed.

2 PROBLEM DESCRIPTION AND PREVIOUS RESEARCH. Space weather is the common term for the set of processes of solar energy transformation and transfer from its origin on the Sun to the interplanetary space. The flow of radiation and charged particles emanating from the Sun has got a complex structure, with several distinctive behavior patterns, such as the 11-year solar activity cycle.
Diversified patterns of the solar energy transfer affects the near-Earth environment, causing significant modifications of the geomagnetic field and the structure of ionosphere. Despite the complexity of the processes, a number of patterns have been identified, and a set of space weather parameters defined (Table 1) that attempt to describe the nature and effects of the space weather dynamics and its effects on geomagnetic field and ionosphere.

Table 1 Space weather-related parameters

Space weather parameter	**Description**
Sunspot number	Sunspot number, measured by Zuerich method
F10.7	Solar radio flux per unit frequency at 2800 MHz, measured in

	Canda at local noon.
Kp index	Planetary K index, relative measure of geomagnetic disturbance
Ap index	Planetary A index, an absolute measure of local geomagnetic disturbance
Dst index	Disturbance storm index, the strength of the ring current above the sub-equatorial region caused by charged particles of solar origin
f0F2	Critical frequency of F2 ionospheric layer
Bx	X component of geomagnetic field
By	Y component of geomagnetic field
Bz	Z component of geomagnetic field
TEC	Total Electron Content

Modern technology-driven civilisation are increasingly exposed to the effects of the space weather, geomagnetic and ionospheric disturbances with the considerable consequences. Those can lead to the risk of disruption or temporal suspension of a wide variety of services supported by systems relying on stable ionospheric and geomagnetic conditions. The systems in question comprise those already established as the essential components of the national infrastructure, such as: pipelines, telecommunications systems, aeronautical systems and satellite navigation systems. Thus, the disturbing effects of the space weather, geomagnetic and ionospheric dynamics may cause severe socio-economic effects on the national level.

According to Maxwell-Faraday equation

$$\oint_{\delta\Sigma} \boldsymbol{E}\cdot d\,\boldsymbol{l} = -\frac{d}{dt}\int_{\Sigma} \boldsymbol{B}\cdot d\,\boldsymbol{A} \quad (1)$$

and Faraday's law

$$e = -\frac{d\Phi_B}{dt} \quad (2)$$

the objects made of conducting materials exposed to variable magnetic field encounter the induction of voltage. Although this phenomenon has got numerous practical applications in electrical engineering, the encounter with it may have unwanted and considerable effects on the performance and operation of distributed systems such as pipelines (corrosion) or aircrafts (effects on navigation and communication instruments, aircraft's structure etc.).
Communication systems, such as: satellite and terrestrial telecommunications systems, financial transactions systems, time systems, and satellite navigation systems, that relies upon predictive and stable propagation of radio waves, may suffer from space weather, geomagnetic and ionospheric disturbances.
Using Appleton-Hartree formula

$$n^2 = 1 - \frac{X}{1 - i\cdot Z - \frac{Y_T}{1 - X - i\cdot Z} \pm \left[\frac{Y_T^4}{4\cdot(1 - X - i\cdot Z)^2}\right]^{0.5}} \quad (3)$$

it can be shown that the ionospheric delay of satellite signals, the major contributor to GNSS positioning error budget, depends strongly on the vertical ionospheric profile N(h) and the Total Electron Content TEC (the number of free electrons encountered by satellite signal on its propagation from satellite to receiver aerials.

$$\Delta t_{iono}[m]=K\cdot\int_0^H N(h)\cdot dh \tag{4}$$

$$TEC=\int_0^H N(h)\cdot dh \tag{5}$$

Additionally, the strong solar wind and enhanced radiation may have destructive effects on maintaining satellites' orbits and on performance and operation of satellite electronic equipment.
Growing dependence on technologies prone to disturbing effects of space weather, geomagnetic and ionospheric disturbances call for establishment of resilience scheme that will successfully mitigate potentially disturbing or destroying space weather effects.

3 TECHNOLOGY RESILIENCE SCHEME AGAINST SPACE WEATHER EFFECTS. Here we propose the Technology Resilience Scheme (TRS) against space weather effects on technology systems exposed and prone to the effects of space weather, geomagnetic and ionospheric disturbances, with the aim to mitigate the risks of disruptive effects on, and the protection of the core technologies embedded in national infrastructure.
The TRS calls for establishment of a four-tier process, as depicted on Fig 1.

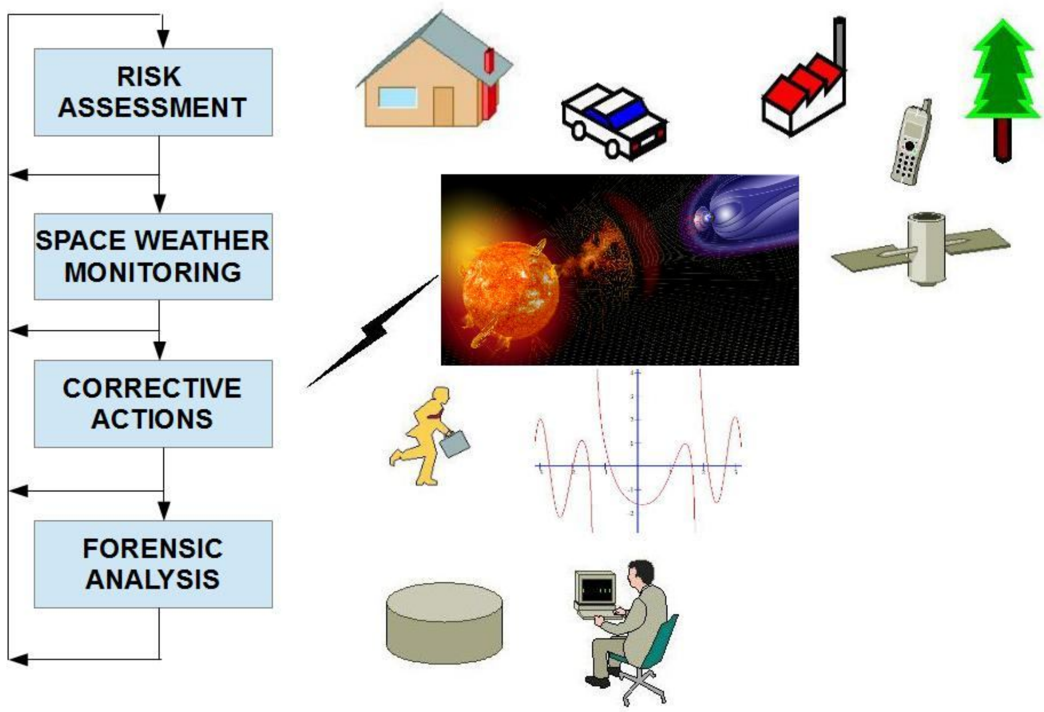

Fig 1 Technology Resilience Scheme against space weather effects

Operators of technology and socio-economic systems at risk from effects of space weather, geomagnetic and ionospheric disturbances should perform a risk assessment procedure with the aim to identify the likelihood and consequences of potential effects on the performance and operation of their systems, as well as to envisage the corrective actions to maintain the essential operations and

protect the infrastructure in case of severe space weather effects.
The continuous process of space weather monitoring and its effects forecasting should be established in order to provide advisory service to the interested parties on the national level. This process is to endorse knowledge building in understanding the dynamics of space weather, geomagnetic and ionospheric effects, with the potential for development of mitigation techniques, proper space weather forecasting and alerting systems, and correction methods to contend the effects of space weather effects on technology and socio-economic systems.
In the situation of severe space weather, geomagnetic and ionospheric conditions, the set of corrective actions should be put up in operation to mitigate the identified potential disturbing effects on technology and socio-economic systems. The set may comprise active technology actions to prevent damages to the infrastructure (switching off the satellites or the other equipment), activation of correction models (for compensation of the ionsopheric delay in satellite navigation, for instance), transition to alternative systems not affected by space weather disturbances, and temporal suspension or limitation of services known to be affected by severe space weather effects (mobile communications, financial transactions).
Finally, the TRS comprises the forensic analysis component, aimed at post-event investigation of space weather, geomagnetic and ionospheric effects on the operation and performance of particular systems and services. With this approach, a continuous knowledge building will be set up, with the potential to improve the risk assessment analysis, propose the improvement of corrective actions, enhance the means for space weather monitoring, and assess the real damage done by particular space weather event.

4 DISCUSSION. The TRS presented in the previous chapter attempts to resolve the problem of space weather effects on the general scale. It integrates the existing resources and calls for establishing those missing in order to facilitate the general awareness of risks and threats developing from space weather effects on technology and socio-economic systems.
In deployment of the TRS in Republic of Croatia, our team at GNSS Space Weather Laboratory, Faculty of Maritime Study, University of Rijeka, Croatia has started to fill in the gaps that prevent development of space weather-resilient systems and services.

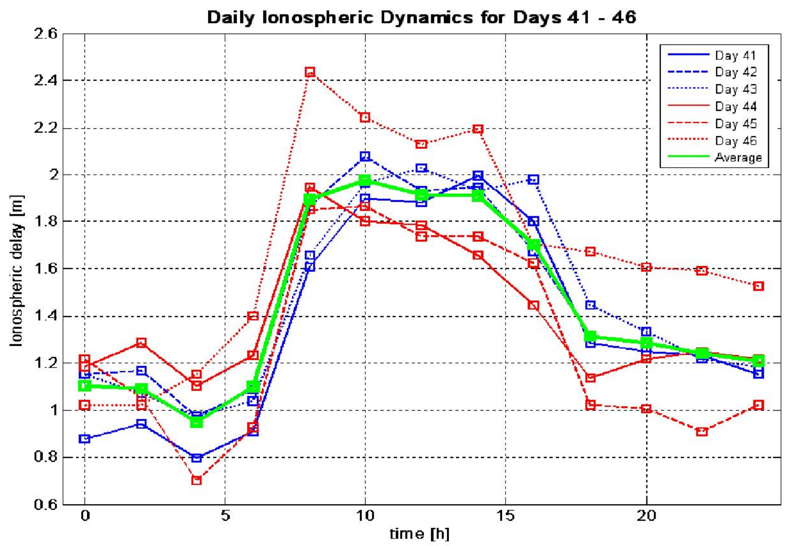

Fig 2 Forensic analysis of an observed space weather event, based on the RINEX data analysis

Our team members continuously develop knowledge and skills necessary to understand, describe and mitigate space weather effects on technology systems. The establishment of GNSS Space Weather Laboratory at Faculty of Maritime Studies in Rijeka, Croatia and Centre for satellite navigation in Baška, Krk Island, Croatia tends to formation of scientific, research and education foundation to endorse continuous monitoring of space weather, geomagnetic and ionospheric dynamics in Republic of Croatia and the Adriatic Sea region. Additionally, it is to facilitate building knowledge on and understanding the local ionospheric processes that affect technology. Finally, it is to develop a community of competent professionals capable of assessing the risks caused by space weather, ionospheric and geomagnetic disturbances through scientific, research and modelling work in international environment with respectable parties abroad.

The GNSS Space Weather Laboratory at Faculty of Maritime Studies in Rijeka, Croatia already maintains a web-site (http://www.ionosphere.hr) with the latest observations and interpretation of measurements in regard to potential space weather risks on technology (especially satellite navigation). Facilities in Baška, Krk Island, Croata and Rijeka, Croatia are to be expanded to shelter a number of passive sensors of space weather, geomagnetic and ionospheric activity (GNSS receivers as sensors included) in order to provide the foundation for development of advanced space weather risk assessment, forecasting and alerting models for targeting and general purposes.

5 CONCLUSION AND FUTURE WORK. Space weather affects increasing number of technology and socio-economic systems essential for modern society. In order to either mitigate or contend risks caused by space weather effects, the Technology Resilience Scheme against the space weather effects is proposed, and its deployment discussed by presentation of related risk assessment, scientific, research and education activities at Faculty of Maritime Studies, University of Rijeka, Croatia.

Future work will be focused on development of understanding the nature of space weather and ionospheric dynamics, space weather knowledge base, local space weather and ionospheric forecasting and correction models, and professional competence in dealing with space weather effects on technology and socio-economic systems, and rising public awareness of space weather.

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REFERENCE

American Meteorological Society. (2011). Satellite Navigation & Space Weather: Understanding the Vulnerability & Building Resilience. Available at: http://bit.ly/rnkRQu.

Cannon, P et al. (2013). Extreme space weather: impacts on engineered systems and infrastructure. Royal Aademy of Engineering. London, UK. Available at: http://bit.ly/11OdBNN

Davis, K. (1990). Ionospheric Radio. Peter Peregrinus Ltd. London, UK.

Filjar, R and Huljenić, D. (2012). The importance of mitigation of GNSS vulnerabilities and risks. Coordinates, **8**, 14-16. Available at: http://bit.ly/Mv4QSc

Thomas, M et al. (2011). Global Navigation Space Systems: reliance and vulnerabilities. Royal Academy of Engineering. London, UK. Available at: http://bit.ly/feFB2i

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