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Extreme Space Weather Events and Military Operations

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Abstract

Extreme Space Weather events can significantly impact military missions and deserve the proper consideration from mission analysis to execution despite of the low probability due to their high impact. Anyway, no agreed definition exists for such phenomena and this affects the relevant messaging, which is a key aspect to successfully coping with exceptional impacts that can partially or totally jeopardise a mission. In this work, we concisely elaborate on key operational requirements.

1. Introduction

Various definitions of Extreme Space Weather Event (ExSWx) events have been used in different contexts, so that a semantic ambiguity still exists and has to be solved. The relevance of ExSWx events for military operations depends on event nature and impact severity [1]. Therefore a clear definition and an effective assessment are desirable to achieve the needed awareness and preparedness.

2. Definition of an ExSWx Event

From a phenomenological point of view, an ExSWx event is typically constituted by a cascade of component events which are nonlinearly coupled and result in energy transfer to Geospace or planetary environments, as will be outlined in Section 3. Hence, we can assume that the definition of an ExSWx event should be based on:

1. A semantics that is consistent both physically and phenomenologically;
2. The energetics of the component events' cascade;
3. The severity of impacts.

This approach should lead to a standardised and agreed definition.

Often in the literature, an ExSWx event refers to the observed:

- Solar flare or a series of solar flares;
- Coronal Mass Ejection (CME) or cascade of CMEs;
- Geomagnetic Storm (GMS);
- Radio Blackout;
- Geomagnetically induced current (GIC);
- Relevant impacts on technological and/or biological systems;
- Whole solar-terrestrial events' cascade.

Any of the above aspects are just a component of an ExSWx event. Hence, all the ones observed and the relevant impacts have to be considered to fully characterise the complex event to avoid a partial identification of causes and effects. Furthermore, the severity of both phenomenology and impacts can be quantised according to thresholds that, when exceeded, define the complex event as extreme.

3. Solar-Terrestrial Weather Phenomena

A scheme of a component physical process that constitute the cascade of physical processes from the source, e.g., the Sun, to the target, e.g., the Geospace is reported in Figure 1. A triggering event affects a source physical system in marginal equilibrium, which is destabilised and then relaxes by originating a primary event at the source as an ensamble of energy carriers. These ones interact with the target physical system, which is, in turn, destabilised and upon relaxation determines a secondary event at the target. A series of nonlinearly coupled physical processes occurring from the Sun to the Geospace represent solar-terrestrial weather phenomena as:

1. Solar weather events (e.g. solar flares);
2. Interplanetary weather events (e.g. CMEs);
3. Geospace weather events (e.g. CME-Magnetosphere interaction);
4. Magnetospheric weather events (e.g. GMS);
5. Ionospheric weather events (e.g. Total Electron Content (TEC) variations);
6. Geospheric weather events (e.g. GICs).

3.1 Solar Weather Events

With reference to Figure 1, at the source one can consider an unstable magnetic topology in a solar active region, which is characterised by sunspot area, magnetic topology and helicity. Magnetic reconnection occurs according to Parker, pile-up or stochastic modes. This instability determines a solar flare, that is characterised, e.g., by the Soft X-Ray lightcurve and peak emission.

3.2 Interplanetary Weather Events

A solar flare can be associated with the acceleration of a CME, i.e., a magnetised plasmoid that propagates through

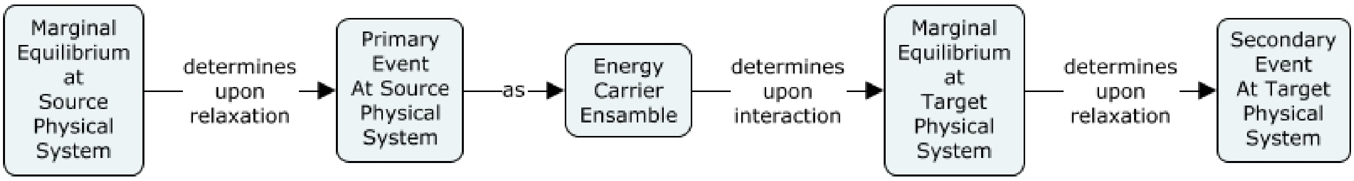

Figure 1. Concept map that outlines the cascade of physical processes underpinning Space Weather events from the triggering to the target physical system.

the interplanetary space as interplanetary CME (iCME). As energy carrier, an iCME can be characterised by mass, dynamics and geometry.

3.3 Geospace Weather Events

The interaction of an iCME with the Magnetosphere determines energy transfer, which can be quantified by the magnitude of ram pressure and hemispheric power, whereas the unstable configuration potential is described by the compression amount and its variation.

3.4 Magnetospheric Weather Events

The unstable magnetospheric configuration determines a GMS, whose global descriptors are the Kp and Dst indices and its typology. The relaxation can originate GICs as secondary events at the target physical system, which are described by intensity and geography.

4. Impact Severity

Specific thresholds can be phenomenologically defined in the framework of relevant impacts to indicate critical or extreme conditions in the affected technological and/or biological systems like, e.g., $THR_{SEPcrit}$ for enhanced Solar Energetic Particle (SEP) fluence, THR_{RScrit} for radio scintillation, THR_{RBcrit} for radio blackouts, and $THR_{GICcrit}$ for GICs. If one or more of the critical thresholds are exceeded, the complex event can be classified as an ExSWx event.

5. Relevance for Military Operations

In the framework of military operations an ExSWx event:

a. Can cause the unavailability of many services on which operations rely on (e.g. communications);
b. Is a mission-critical factor, as it can completely jeopardise specific operations despite of the availability of backup/mitigation techniques;
c. Forecasts, nowcasts and prompt warnings are a must.

Hence, in a military framework, SWx events must be characterised by their probability and severity class as well as by their relevance to a specific mission [1]. This analysis leads to a table as in Figure 2. Furthermore, the mission analysis (Figure 3) must consider the services on which it is based on, their criticality for the success of the mission and their availability, which can be affected by SWx events according to the assessment table.

EVENT		RELEVANCE OF IMPACT FOR MISSION			
		Unaffected	Important	Essential	Critical
PROBABILITY	Low	0	1	2	3
	Medium	1	2	3	4
	High	2	3	4	5
	Very High	3	4	5	6

Figure 2. SWx event risk assessment and management table in the military framework [1].

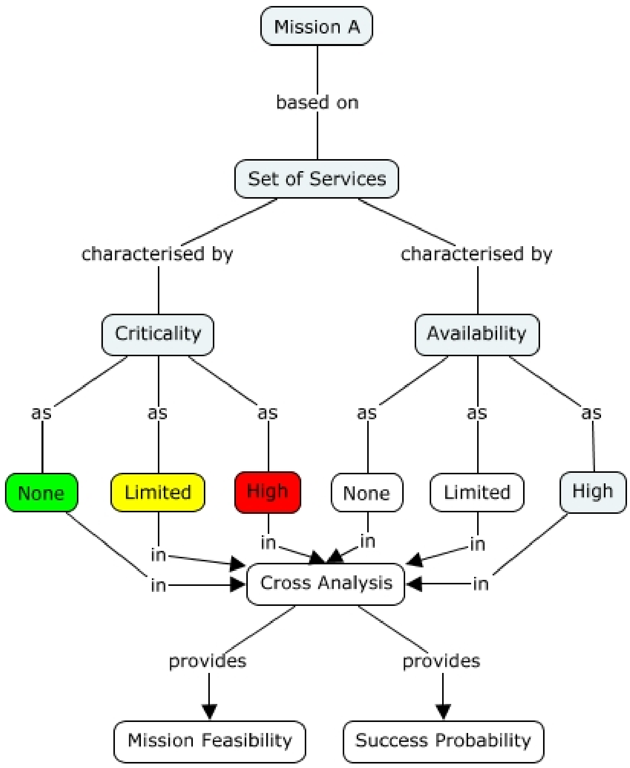

Figure 3. Mission analysis based on service availability [1].

All the segments of a space system can be impacted by SWx [1,2]. For instance, Figure 4 depicts the satellite segment sub-systems of a space system that are affected by SWx events. They are respectively payloads, telemetry, attitude and orbit controls, structure, thermal controls and power ones. Similarly, Figure 5 depicts the ground-system segment sub-systems impacted by SWx events such as communications, computing, power, structure, thermal control ones. One or more can be severely affected by an ExSWx event and this can prevent the space system from successfully operating, i.e., from providing the services required by the mission target. For instance, positioning, navigation and timing services can be mission-critical.

In the case of ExSWx events, the impact can be so heavy to cause even permanent damages capable to make some sub-systems partially or permanently unusable [3]. New generation satellites are designed to be able to survive to very high energetic particle fluxes and this makes them very robust and reliable in service provision continuity. Anyway, ExSWx events can be so intense that the energy carriers might exceed the safety design thresholds.

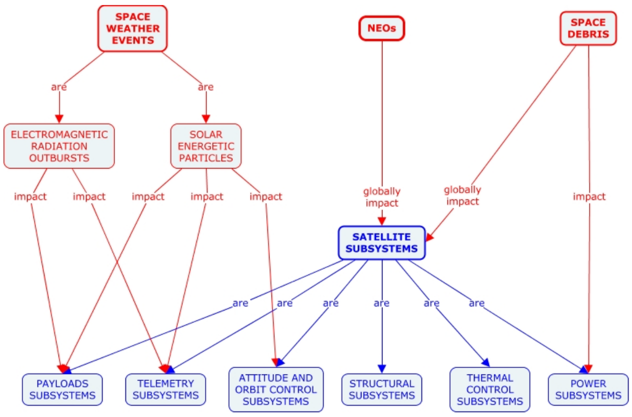

Figure 4. Satellite segment sub-systems affected by SWx events [1].

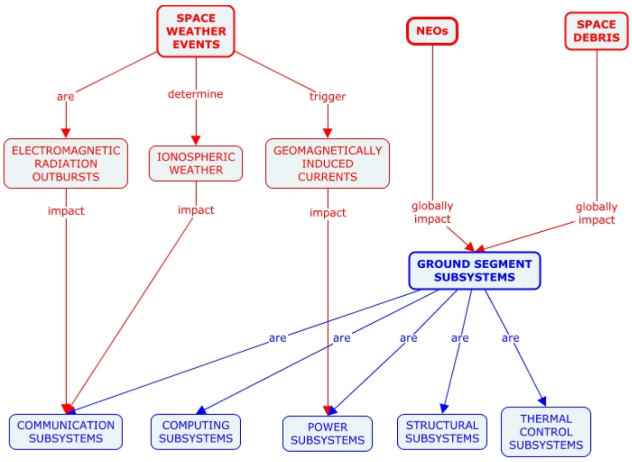

Figure 5. Ground-system segment sub-systems affected by SWx events [1].

6. Monitoring and Warning Requirements

SWx events have typically a global nature, i.e., they affect the Geospace, but the impacts can be geographically different by extension and intensity. Furthermore, it is expected that an ExSWx event will originate a variety of high intensity impacts at a global level. Hence, a key aspect to cope with it is the availability of an effective monitoring, nowcasting and forecasting network in space and on the ground, that is able to detect and warn about precursors, phenomena and possible impacts both at global and at regional level, being the latter particularly relevant to military operations [1] (Figure 6).

On the other hand, no ISES (International Space Environment Service)-like dedicated military network exists, e.g., for the North Atlantic Treaty Organization (NATO). In fact, in the framework of NATO, national facilities can be shared or not with Partners according to the principle of national sovereignty preservation. Hence, monitoring and warnings are derived from:

a. Governmental/institutional public services;
b. Non-public services (Department of Defence (DoD)-customised public services);
c. Classified services (DoD-proprietary).

Many partner nations have developed civil, e.g. Regional Warning Centres of ISES, and/or military SWx centres and rely on them for conducting military operations. The other partner nations are totally dependent on the services provided to them by the allies.

The characteristics of SWx information for successful operations can be summarised as follows [1]:

a. Target-user-dependent;
b. Prompt;
c. Essential;
d. Comprehensive;
e. Standard;
f. User-friendly;
g. On global effects;
h. On regional effects;
i. With alerts and warnings with nowcasts and forecasts.

In fact, it has to be:

a. Tailored according to the expertise of the user (e.g., operator, specialist, soldier);
b. Adequately timed;
c. Without redundancy that can be misleading;
d. Covering the relevant phenomenology and impacts;
e. Compliant with an agreed messaging standard;
f. Easy to understand;
g. Descriptive of the globality of phenomena and impacts;
h. Descriptive of the locality of phenomena and impacts;
i. Constituted by alert and warning messages that contain nowcasts and forecasts.

The listed requirements are key ones to allow for coping with ExSWx events in any military situation such as, e.g., support of civilians in natural hazards or peacekeeping activities, because proper messaging is the basis for a coordinated and effective response as prescribed by awareness and preparedness about the phenomenology, its impacts and the mitigation techniques [1,2,3].

An unclassified multi-level messaging can be made available through a dedicated web site like the prototype one studied in [1], which reports the status of the three segments of a space system in a concise way (Figure 7).

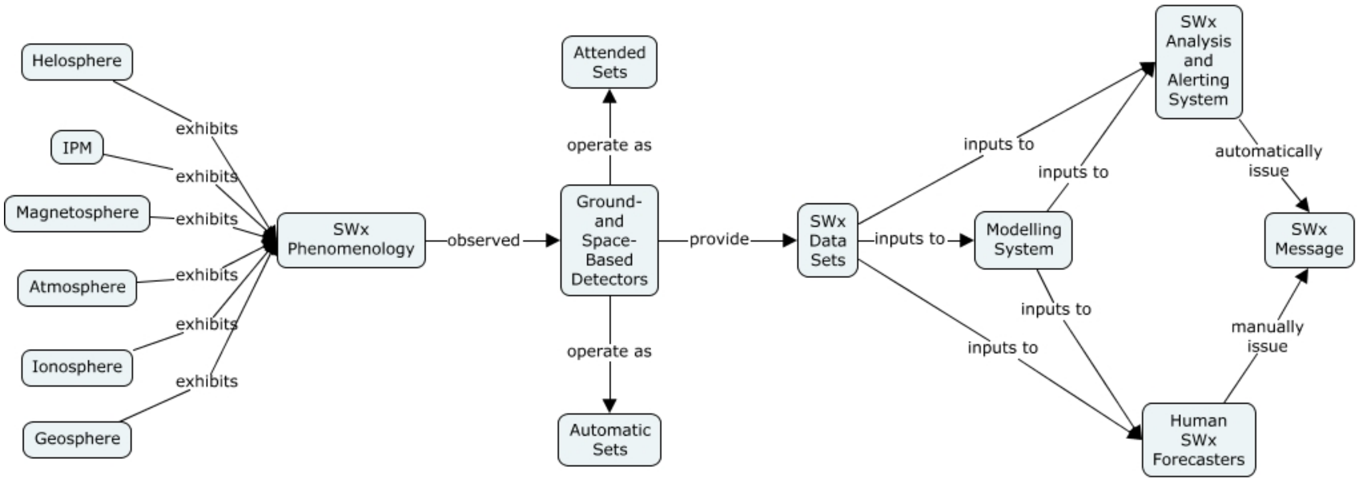

Figure 6. General scheme of SWx monitoring, modelling and predicting that result in the relevant messaging [1].

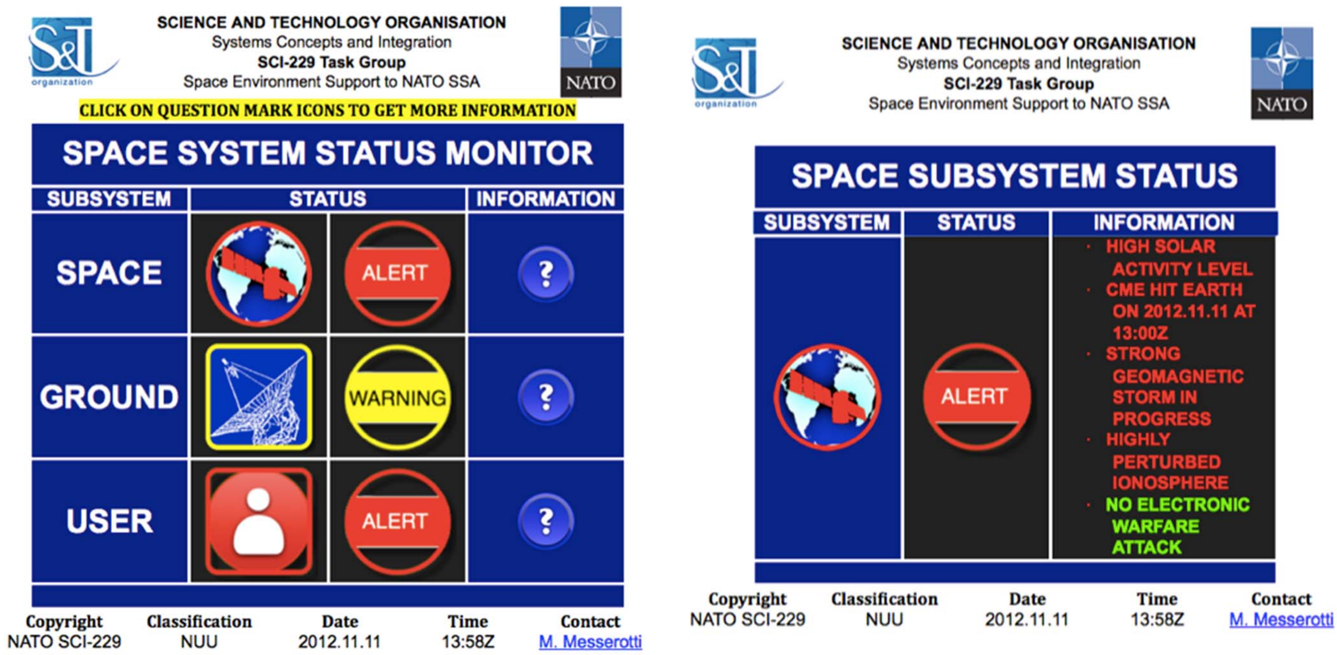

Figure 7. Space System Status Monitor (S3M) prototype web site, developed for NATO [1]. The homepage summarises the status of the three segments of a space system (left panel). A detailed but essential message that clarifies the alert status for the space segment is reported in the dedicated page (right panel).

8. Acknowledgements

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9. References

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