Space Weather & Internet Resilience
the Case of the Submarine Optical Cables

Abstract

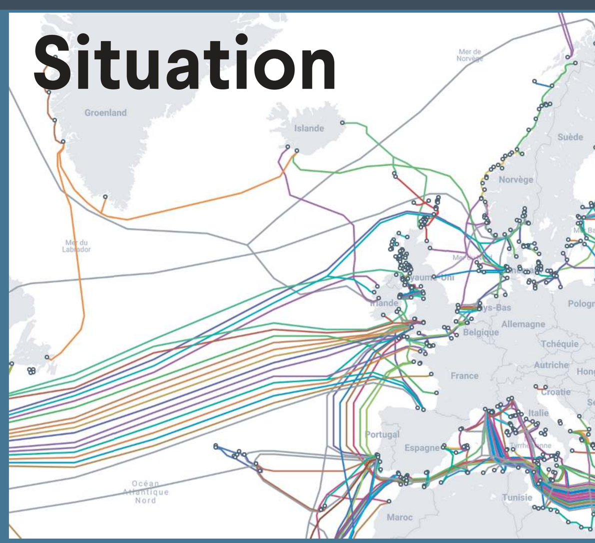
In 2021, a major scientific debate opened up around the possibility of an "Internet apocalypse" linked to extreme geomagnetic storms, in which the GICs generated during a Carrington-type event could cause large-scale damages to optical signal repeaters on transoceanic submarine cables. However, this fear is not universally shared, not for example by Google researchers.

At regulatory level, geomagnetic storms and extreme GICs are not considered in the reliability standards for submarine optical cables, neither in national standards (e.g: USA) nor in international standards. At technological level, specifications for submarine optical cables are not centralized, making it difficult to model the current network correctly. However, the current trend is towards increasing reliability of submarine optical cables via some new standards: power supply equipment redundancy from one end of the transoceanic cable to the other, increased capacity of Zener diodes protecting against GICs, greater resilience of SDM optical signal amplification systems, also. At scientific level, consensus is emerging around the importance of near shore auroral electrojet induction phenomena, which are deemed significant at depths of less than 600/1000m.

Our research has led to the main vulnerabilities summarized in this poster:
- Coastal site effects, which amplify GICs, are not factored when selecting cable landing sites.
- WDM optical signal repeaters equipping a large part of the current network, are the most vulnerable, as many are equipped with Zener diodes rated at 200 A, which may not be sufficient to withstand a Carrington event (200 to 400 A in extreme GIC near the coast).
- SDM technology repeaters, which are beginning to be deployed, can afford 700 A, which may be sufficient for a Carrington event, but insufficient for a millennial event.
- Data relating to the grounding (via the sea) of submarine optical cables, which enable GICs to be evacuated, are not centralized and open, preventing correct modeling of GICs on the network.
- Taking into account a return period of 200 years as that of a Carrington event is far too restrictive, given the crucial importance of the Internet in our societies.

To improve S&T research on the resilience of the Internet to extreme geomagnetic storms, it is first necessary to centralize all specifications around submarine optical cables in an open information system. Studies should be carried out into the creation of priority data transport routes, resilient to an extreme ten-millennial solar event, to ensure the continuity of essential and vital communications. Finally, we need to study the implementation of large-scale action plans for the network (alerts, emergency management including plans to reduce operating power, rapid recovery and network refurbishment).

Situation



EUROPE

3 optical cable repair ships in Europe: France: in Brest and in La Seyne-Sur-Mer, Italia: in Catania. (+ UK, non EU: in Portland).

Number of landing optical cables in mainland EU: around 300

Repairing capacity is inadequate for a fast recovery from a large-scale adverse event.

However, only 18% of the capacity of those cables are being exploited.

WORLD
- 1,3 million Km of submarine optical cables,
- 532 operating cables systems & 77 planned systems,
- 95% of internet traffic, 99% at intercontinental level,
- Submarine optical cable life span: 25 years,
- Manufacturing process time: 2 to 3 years,
- Submarine optical cable cost: hundreds of millions ,
- Average ocean depth: 3 682m.
- Repairs: during weeks at prohibitive costs,
- Production, installation and maintenance of submarine optical cables: only few multinational firms qualified (ASN, Subcom, NEC, Hengtong, Orange Marine, Global Marine Systems...),
- 500 operating companies, mostly in telecom sector,
- Cable operation tends to be concentrated within content supplier firms (e.g: GAFAM).

(No) Regulation

Submarine optical cable regulations depend on Telecommunications National Regulating Authorities.

National

United States (70 à 80% of all internet trafic):
- Communications Security, Reliability and Interoperability Council (CSRIC) .
- Congressional Research Service : " Protection of Undersea Telecommunication Cables: Issues for Congress " - 2023.

International

International Cable Protection Committee:
"Document of Best Practice" - 2023
European parliament:
"Security threats to undersea communications cables and infrastructure – consequences for the EU." - 2022 .

No mention is made to geomatic storms and GICs in those documents.
No standard cable specifications or standard landing sites available.

Physics

- Deep ocean acts like a shield to the cable against induction phenomena (Chakrabarty and al, - 2022), from 600-1000m of depth (Thinn et al - 2022).
- Sections of the cable in the submarine continental plateau generate electromagnetic fields twice as high as those of the deep ocean. However, this sections only represent a small part of the path (11% in the Atlantic ocean) so, it is the cable length of the deep ocean section that leads induced electromotive force between Earth potential at the ends of the cable (Boteler - 2024).
- The difference in potential between the two earth connections of the cable power feeding equipment is the first induced electromotive force driver to the cable (Boteler - 2024).
- Voltage disruption is proportional to the electromagnetic field's interferences (Mecozzi - 2022).
- Geomagnetic interferences and GICs will be the highest between 40 and 60° of geomagnetic latitude for a hundred-year event (Pullkinen et al. - 2021).
-30 to 40% of landing points happen to be in exposed latitudes › 40° (Jyothi - 2021).
- Cable extremities are not equally affected by geomagnetic interferences because large transoceanic cables can cover several time zones (Mecozzi - 2022).
- Major geomagnetic storms are usually characterized by the weakening of the geomagnetic field and by a drop in the required voltage, which does not hamper the operation of power supplying equipments that are able to adapt by decreasing their power supply (Mecozzi - 2022).

However, this position does not solve the GIC intensity issue which may be damaging to equipments.

Normal operation

Total Voltage= I.Rcable+n.Vrepeaters= Vpfe1-Vpfe2-VearthPfe1-VearthPfe2

$R=0{,}8\ \Omega$/km approx.
I=1A approx.

Transient regimes › - 600m depth

20 to 100 years: 2,5 V/km, 50 A
100 years: 5 V/km, 100 A
› 100 years: 10-20 V/km, 200-400 A

Cable induced voltage

$V_C = \mathcal{E}_C + U_A - U_B$

U_A = earth potential at the end A of the cable
$\mathcal{E}_C$ = the induced electromotive force induced by the magnetic field variations directly in the cable

100-year geomagnetic pulses at coastal sites

Thomson et al. (2011), "Quantifying extreme behavior in geomagnetic activity, Space Weather, 9, S10001
Author of the map : I-Resilience - 2024.

At similar geomagnetic latitude, some coastal magnetometers react with much less intensity than others to a hundred-year geomagnetic pulse.
Consequently, some coastal sites are more suitable than others to the installation of submarine optical cable terminations.

No internet disruption during events of -400nT (DST index)

Internet is calibrated for -400 nT DST index storms (may 2024, -412 nT and Oct 2023, -383 nT): no cable fault. The TAT-8 transatlantic cable, first transoceanic optical cable has not suffered any damage following the 1989 storm (DST -589 nT). However, this observation cannot be generalized as the TAT-8 lands in geomagnetically relatively stable area (HAD magnetometer)

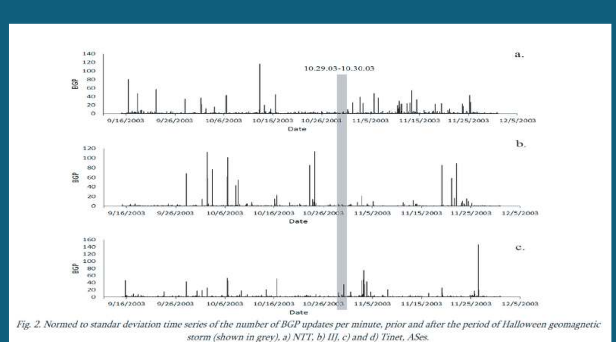
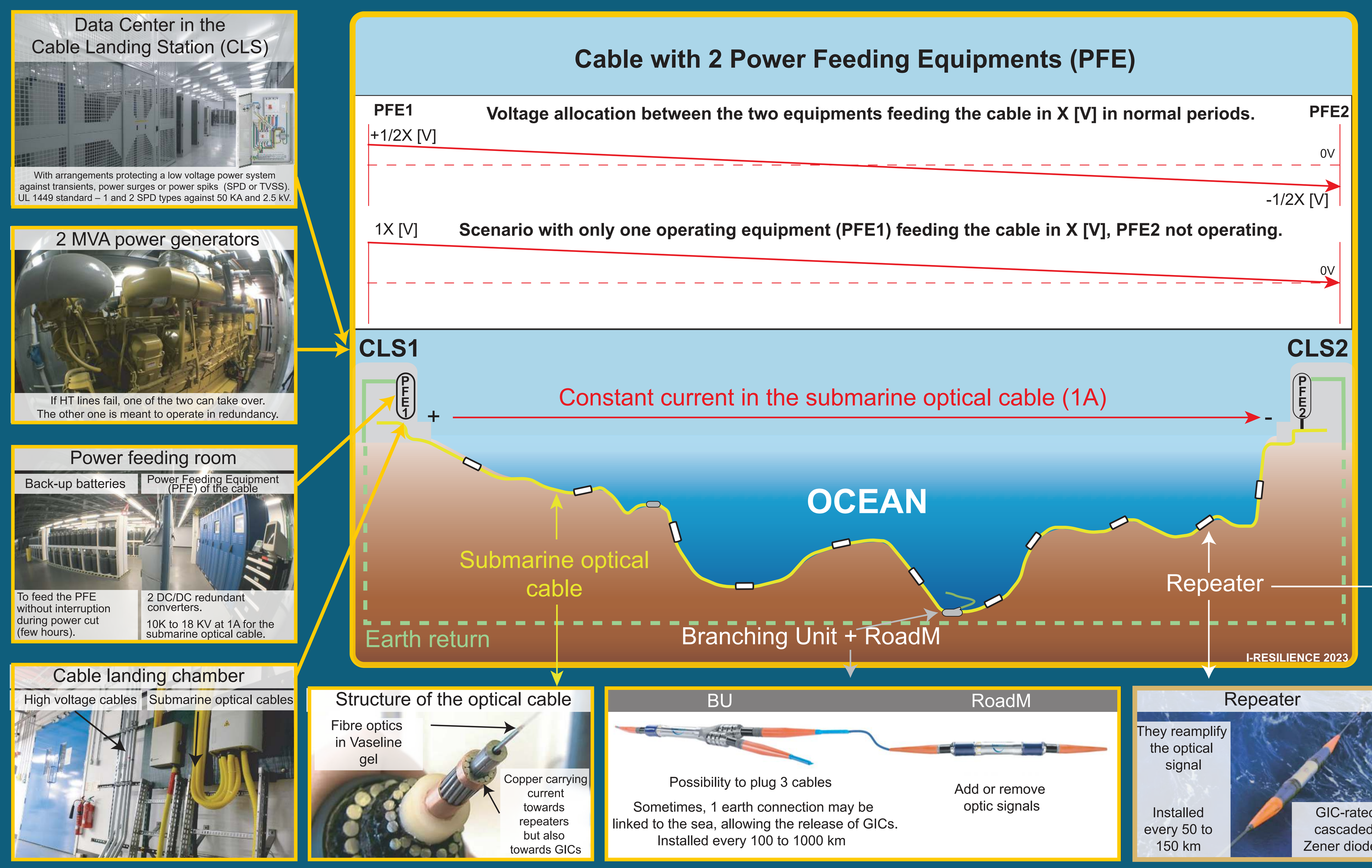


Fig. 2. Normed to standar deviation time series of the number of BGP updates per minute, prior and after the period of Halloween geomagnetic storm (shown in grey), a) NTT, b) IIJ, c) and d) Tinet, ASes.

T Matcharashvili, et al. « Analysis of the Relation Between the Variation of ASY-H Geomagnetic Indices and the Character of Internet Interdomain Routing During the 2003 Halloween Geomagnetic Storm« .
Mikheil Nodia Institute of Geophysics of Ivane Javakhishvili Tbilisi State University, Tbilisi, Georgia. 2023.

Operation of the transoceanic optical cable during calm space weather



Ideal redundances

- Each PFE can feed the cable through, from end to end.
- Each PFE has two DC/DC redundant converters.
- Each CLS has two redundant power generators.
- Each CLS has redundant battery pools.
- The operator can reroute traffic towards another cable.
- The operator has SDM repeaters instead of WDM repeaters

Classic WDM repeater

Transforms the optical signal into electric signal, reamplifies the signal and turns it into optical signal.

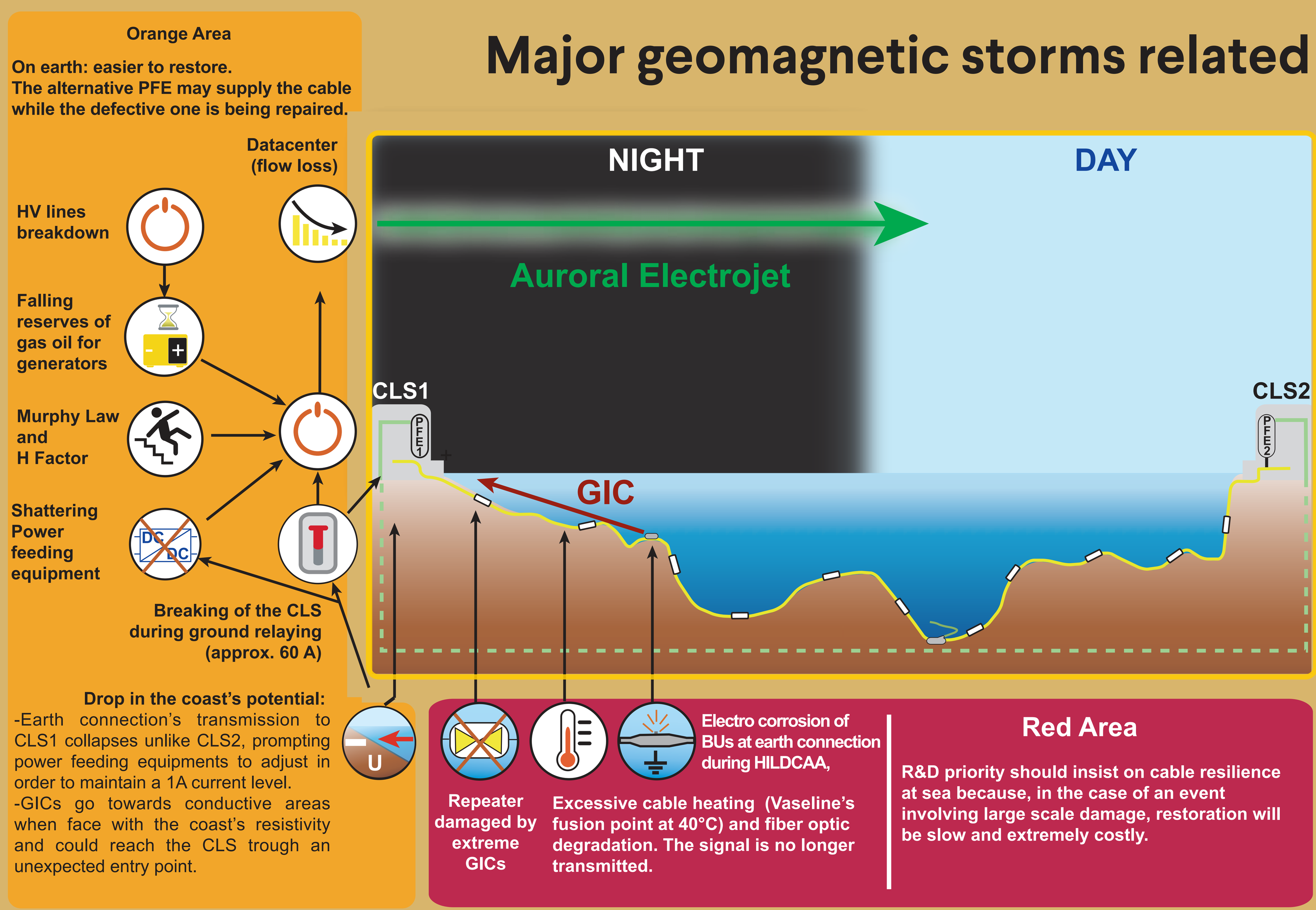
- Latency during conversions.
- If one component is defective, the cable will not operate.
- **Rated 200 A** for the best of them.

New generation SDM repeater

Ion-boosting laser pumps in the fiber, without conversion into electric signal

- No latency.
- Redundant laser pumps: a pump can stop operating, the other ones may increase its capacity.
- **Rated 700 A** for the best of them.

Major geomagnetic storms related risks



Unknown elements

- Submarie optical cables have never been submitted to real life stress test during a major geomagnetic storm (DST index below -600 nT).

- Some cable landing sites, as well as oceanic paths, have not been chosen based on their tendency to mitigate GICs and inductions.

- Submarine optical cable specifications documents are very difficult to find. It is therefore estimating repeater requirements for each cable type is a subtle task, especially Zener diode cascade capabilities to counter GICs.

- Because of electro corrosion, some cables no longer have earth connection in BUs. It is difficult to identify them.

- Interconnection of cables from different operators are also unknown.

- CLS redundancy levels are not centralized either.

- Some close-reaching submarine optical cables which do not need repeaters, still coated in copper sheath, are likely to transmit GICs.

- Some highly competitive cable producers save on the quality of cable insulators and armour.

Strengthening the resilience of the submarine optical network

Experiments on end-of-life cables

The aim here is to perform measurements and test on real cables which have been freshly disconnected for financial reasons, however they are still operational and actionable on CLS:

- Test cable reaction at different power intensities until the repeaters fail.
- Measure electro-corrosion of optical cable earth connections on simulated HILDCAA events.
- Establish cable heating level at different power intensities and voltages.
- Study electromotor force behavior by simulating differences in potential for cable earth connection.
- Estimate the efficiency of optical flow derivations on old cables after a major event involving damage.

The overall collected data will be used for S&T research and to estimate the network resilience, advise cable operators and standardize the most sensitive equipment.

Network modeling with the challenge of GICs

The aim is to centralize the most precise specifications on submarine optical cables to better model the network, this includes:

- Equipment operating ranges, on earth or at sea,
- Spacing between each repeater and each BU,
- Possible optical flow derivations between different cables,
- Precise enough optical cable routes on the continental talus or in deep sea to model induction effects or impedance,
- Redundancy levels in CLS for each cable,
- Years of cable construction and operation,
- Length, resistance and other physical characteristics,

The objective would be to link to the Telegeography database of submarine optical cables with these specifications of as many submarine optical cables as possible so as to make estimates on the technology used for the cables which data were missing.

Design of a 10,000-year geomagnetic storm-proof route

Given the utmost importance of internet in our societies, it should be possible to share basic and capital information at all times.

If it seems virtually impossible to standardize the whole submarine network in a midterm timeline, especially if it is aimed to make it resilient to a 10,000-year event such as a Miyake event, it is however possible to design a global sub-network linking all continents and islands through secure pathways while limiting the number of repeaters to a minimum in areas where submarine topography mitigates electromagnetic inductions and GICs.

Such an operation could be carried out at European scale including overseas territories or at United Nations scale. It would then be possible to channel through all information from rescue and emergency centers but also certainly all SMS and voice communications from around the world to ensure a minimal resilience to this type of event.

R&D lessons drawn from that hyper-resilient infrastructure would help establish prime submarine optical cables routes.

Large scale action plan design

- **Warning Plan**: space meteorology forecasts, indices (e.g: dB/dT of magnetometers close to cable landing sites), unreachable submarine cables (e.g: Nautilus, multi-channel intelligence), internet overall resilience (e.g: BGP warnings) should be available on NOC dashboards (Network Operations Centers).

- **Emergency Management Plan**: operators may opt for rerouting traffic towards less GIC-exposed latitude routes or even to temporarily disable some of their most vulnerable cables.

- **Rapid Recovery Plan**: On a large-scale event involving damage, instead of proceeding by individually repairing each cable at sea, it could be preferable to redirect lost optical flow towards other nearby cables by creating new interconnections between cables from different operators. National Telecommunications Regulatory Authorities could supervise such a emergency provision until total network recovery. Also consider reenabling old but still operational cables to increase available bandwidth.

- **Prevention Plans**: make sure equipment redundancy is maintained in NOCs and CLSs, carry out regular exercises, design a tool that could help estimate the most intense coastal GICs on major events to better select suitable cable landing sites or inform operators of the most intense GICs expected to affect their site.

Conclusion

These plans can only be achieved through collaboration between international networks (E-SWAN, ISES, etc.) specializing in space weather and space climate, in conjunction with private operators of submarine cable technology, and specialists in major risk prevention and in the resilience of human organizations to natural and technological disasters and health emergencies, such as I-Resilience.

Bibliography

Cédric Moro - 2024
I-RESILIENCE LTD
i-resilience.com
cedric.moro@i-resilience.fr
Contacts