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Prepared by WGI
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Strengths, Weaknesses, Opportunities and Threats (SWOT) Analysis of Low Latency Data Access from LEO Meteorological Satellites

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1 WORKING PAPER SUMMARY:

The core meteorological satellite systems in LEO orbits, and other operational satellite systems where applicable, should ensure low latency data access of imagery, sounding, and other real-time data of interest to users. Application areas where low latency and availability is suitable include Severe Weather Monitoring, Nowcasting and Short- and Medium-Range Numerical Weather Prediction. Other application areas could also benefit from very low latency products, e.g. ionospheric monitoring.

Today, LEO meteorological satellites have two distinct services for providing low latency data to users:

- Global service: where the full orbit data is stored on-board and served at the pole(s)
- Regional or local service: real time dissemination of instruments data to a network of direct broadcasts stations.

The goal of this CGMS paper is to analyse the Strengths, Weaknesses, Opportunities, and Threats (SWOT) of current LEO weather satellites systems to identify how low latency data access solutions could help in improving timeliness globally.

This SWOT analysis paper follows a previous CGMS paper [CGMS-51-WGI-WP-06] which focuses on low latency data access solutions opportunities for LEO weather satellites systems.

2 CONTEXT AND SCOPE

Today, the LEO meteorological satellites families of CGMS agencies have two distinct services for providing data to users:

- Global service: where the full or half LEO orbit data is stored on-board and served at the pole(s). This mission provides global coverage at high latency (> 1 hour);
- Regional or local service: real time direct broadcast dissemination of data to a network of direct broadcasts stations. This mission provides regional coverage at low latency.

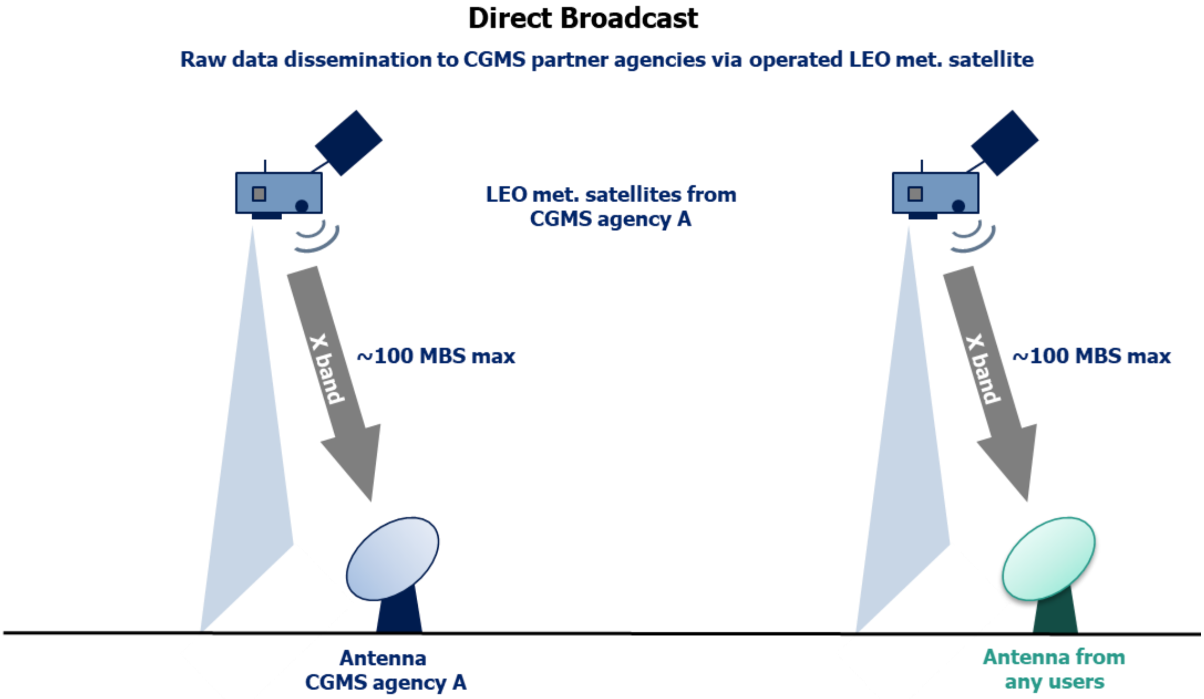

Figure 1: Current direct broadcast data downlink solution considered for SWOT analysis

The global and regional data services serve different communities, which have different requirements, needs, knowledge and post-processing capabilities. In particular, the regional users only receive direct broadcast local data which is available with almost no delay for processing. Direct Broadcast community is engaged in the DBNET network with exchange of regional data with the GTS (soon to be replaced by WIS 2.0).

Direct Broadcast systems will be part of the next generation of the CMA, EUMETSAT and NOAA satellites as shown on Table 1.

CGMS agency	Satellite Series with Direct Broadcast System	Launch window	End of Operations
CMA	FY-3F, G, H	2022 - 2031	~2036
NOAA	JPSS2, 3 and 4	2022 – 2038	~2043

EUMETSAT	EPS-SG	2025 – 2037	~2042
	EPS-Sterna	2024 – 2029	~2042

Table 1: Confirmed Direct Broadcast Agenda for CGMS agencies

The goal of this CGMS paper is to analyse the Strengths, Weaknesses, Opportunities, and Threats (SWOT) of the current LEO weather satellites systems to identify low latency data access solutions that could reduce the time between data acquisition and on-ground availability globally.

This CGMS paper is structured as follow:

- Section 3: SWOT Analysis Summary Table;
- Section 4: Strengths;
- Section 5: Weaknesses;
- Section 6: Opportunities;
- Section 7: Threats;
- Section 8: SWOT Conclusion.

3 SWOT ANALYSIS SUMMARY TABLE

S Strengths	W Weaknesses	O Opportunities	T Threats
Maturity: S1. Well established LEO weather space segment S2. Well established ground segment worldwide for regional and global missions S3. Well established coordination at CGMS, DBNET and WMO levels. S4. Well established standards and best practices S5. Well established data distribution mechanisms to users **End2End ownership of data chain:** S6. Owned space and ground equipment, giving more control over assets. Limited reliance on private sector in the data chain.	**Downlink and Latency:** W1. High latency over regions without direct broadcast, e.g. gap over oceanic regions W2. Duplicated products between regional and global products W3. Data rate limitation in direct broadcast X band **Cost:** W4. Owned / dedicated ground equipment leading to higher costs. W5. Communications links to multiple ground stations required. **Commanding:** W6. No uplink outside polar regions W7. Limited monitoring of space assets outside of polar regions	**GEO relay services:** O1. Global availability of data worldwide through GEO relay constellation. O2. Maturing market with Inmarsat, SES Astra and many others **LEO relay services:** O3. Global availability of data worldwide through LEO relay constellation. O4. Low maturity, many new markets appearances. **Ground stations as a Service:** O5. Regional availability of data through a global network of ground stations as a service. O6. High maturity. **Satellite Platform:** O7. Built-in GEO relay transponder O8. Satellite Platform as a Service (SPaaS), covering launch to operations. **Cloud services:** O9. Complete suite from raw data to products available within most latency requirements. O10. User internet capability will determine volume and latency.	**Dependence on private sector:** T1. Reliance / dependence on a commercial service for the end2end ownership of data chain T2. Volatile relay satellite operators market **Cost:** T3. Relay constellation bandwidth cost, particularly GEO **Frequency protection:** T4. Relay constellation increase pressure on the frequency spectrum **Security:** T5. For SPaaS Security risk via uplink commands to CGMS satellite. **Coordination & Standards:** T6. Role of CGMS inter agency coordination unclear for data exchange mechanism which may change (e.g. via cloud?) T7. Little to no standards for inter-satellite communications.

4 STRENGTHS ANALYSIS

Maturity

S1. Well established LEO weather space segment:
Direct broadcast is a well mature technology, see Table 2 below for historical launch of LEO meteorological satellites and Table 1 for future program:

CMA	EUMETSAT	NOAA
FY-3A (2008) FY-3B (2010) FY-3C (2013) FY-3D (2017) FY-3E (2021) FY-3G (2023) FY-3F (2023)	Metop-A (2006) Metop-B (2012) Metop-C (2018)	NOAA-1 (1970) NOAA-2 (1972) NOAA-3 (1973) NOAA-4 (1974) NOAA-5 (1976) NOAA-6 (1979) NOAA-7 (1981) NOAA-8 (1983) NOAA-9 (1984) NOAA-10 (1986) NOAA-11 (1988) NOAA-12 (1991) NOAA-13 (1993) NOAA-14 (1994) NOAA-15 (1998) NOAA-16 (2000) NOAA-17 (2002) NOAA-18 (2005) NOAA-19 (2009) S-NPP (2011) NOAA-20 (2017) NOAA-21 (2022)

Table 2: History of LEO meteorological satellites from CGMS agencies with Direct Broadcast

S2. Well established ground segment worldwide for regional and global missions:
Direct broadcast reception allows for almost full coverage of the globe as shown on Figure 2 below:

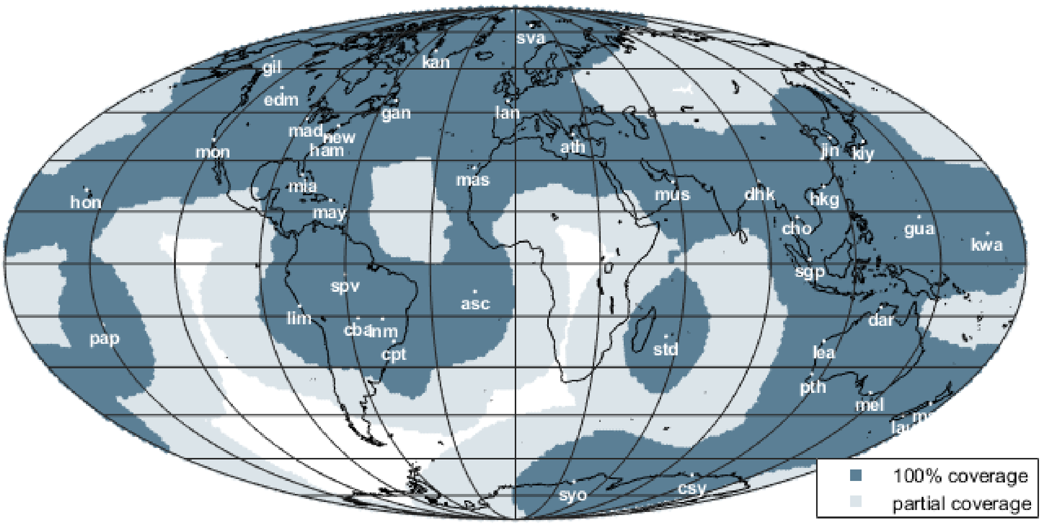

Figure 2: DBNet-ATOVS coverage in October 2022

Infrastructure for acquisition of global data has also been operational for at least a decade for each CGMS agencies.

S3. Well established coordination at CGMS, DBNET / WMO levels.
CGMS, founded in 1972, holds the Working group I (WG I) "Satellite systems and operations" which has for objective to address technical and operational aspects of direct broadcast services (present and future) of mutual or global interest for the CGMS agencies. See: https://cgms-info.org/about-cgms/working-group-i/

WMO DBNET community, see: https://community.wmo.int/en/activity-areas/wmo-space-programme-wsp/dbnet

S4. Well established standards and best practices
CGMS operator uses the CCSDS standard for data formatting, see https://public.ccsds.org/default.aspx.

CGMS best practices are also published or proposed to support exploitation of LEO meteorological satellites from CGMS agencies:

- CGMS Agency Best Practices in support to Local and Regional Processing of LEO Direct Broadcast data (endorsed by CGMS-48, May 2020) [CGMS/DOC/18/1008274];
- Proposed Best Practices for the Coordination of Data Acquisition for Low Earth Orbit Satellite Systems [CGMS-50-NOAA-WP-05-PPT].

S5. Well established data distribution mechanisms to users
Global data distribution of LEO meteorological satellites mechanisms are coordinated by the WMO, see for example:

- https://community.wmo.int/en/activity-areas/global-telecommunication-system-gts;
- https://community.wmo.int/en/activity-areas/wis.

End2End ownership of data chain

S6. Owned assets:

Owned space and ground equipment, giving more control over assets. Limited reliance on private sector in the data chain.

CMA:

EUMETSAT:

The METOP and EPS-SG satellites series are owned and operated by EUMETSAT. Global and regional data are acquired via dedicated assets in Svalbard (global) and through the EARS stations for direct broadcast acquisition, see Figure 3.

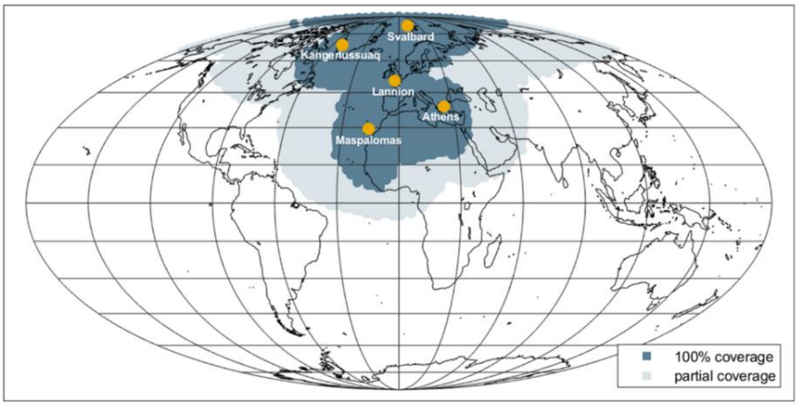

Figure 3: EUMETSAT owned ground segment assets: Svalbard ground station for global mission (left), EARS stations for direct broadcast acquisition (right)

NOAA:

The JPSS satellites are owned and operated by NOAA, the POES satellites are owned by NOAA and operated by a third party contractor (Parsons).

Global and regional data are acquired via dedicated assets in McMurdo and Svalbard (global) and through the DBRTN stations for direct broadcast acquisition, see Figure 4.

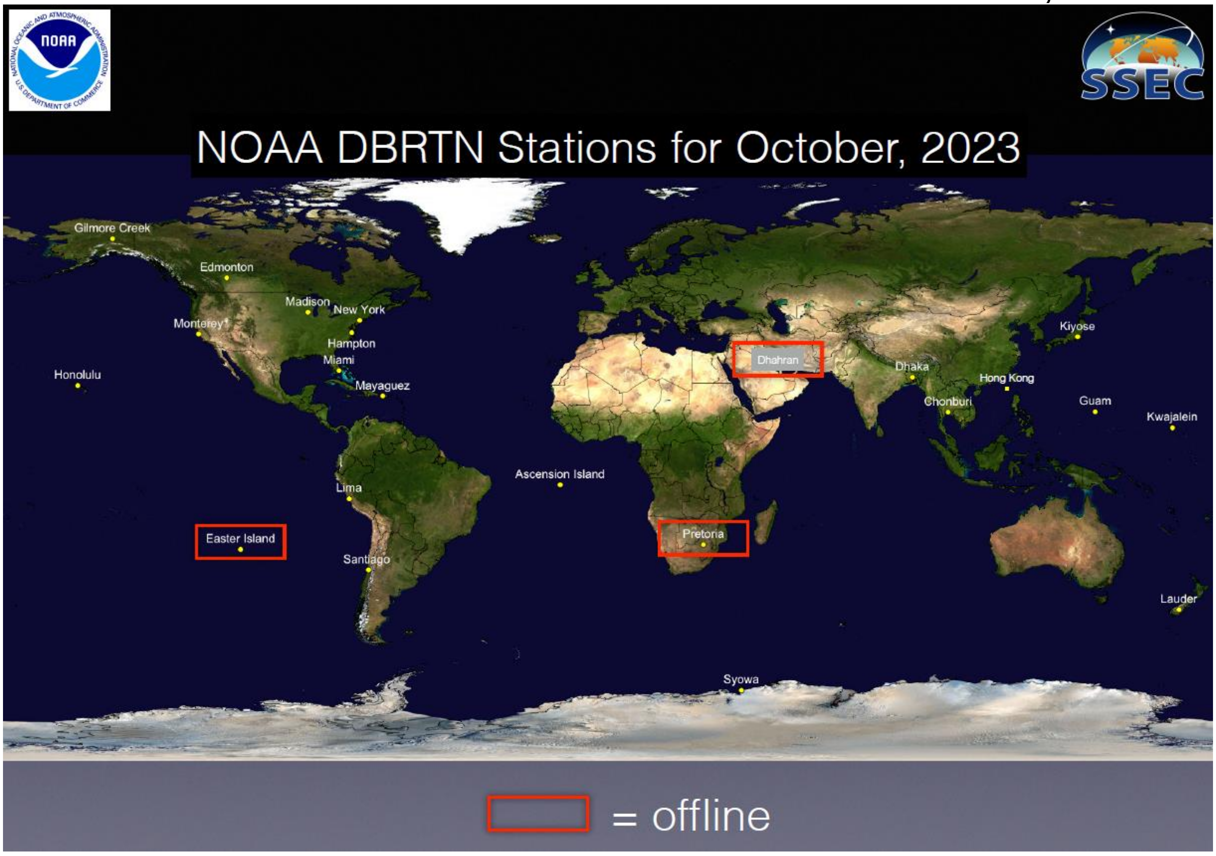

Figure 4: NOAA direct broadcast reception network

5 WEAKNESSES ANALYSIS

Downlink and Latency

W1. High latency over regions without direct broadcast, e.g. gap over oceanic regions

As depicted on Figure 2, gap in direct broadcast acquisition can be found in oceanic regions, mainly Pacific Ocean and over the African continent.
The SAWIDRA project is a recent initiative to deploy direct broadcast capability to the African continent and fill the current gap, so continental gaps can be expected to decrease within the next decade.

W2. Duplicated products between regional and global products

A limitation of the current LEO meteorological satellites systems is that the same data can be disseminated twice, first dissemination being via direct broadcast and then via the global products or full orbit dissemination. Data duplication can also occur between regional stations where regional data acquisition overlap.

Numerical weather predictions overcome this limitation by having built in functionality to automatically remove data duplicate.

W3. Data rate limitation in direct broadcast X band

In response to the continuous increase in instrument data rates, a migration from L-band (1.8 GHz) to X-band (7.8 GHz) based direct broadcast is currently ongoing. However, even while this migration is still ongoing, indications are that the latest generation of satellites is gradually reaching the limits of the current conventional design of the direct broadcast downlink in X-band.

With the potential of even higher data rates from future polar orbiting satellites, this working paper outlines a number of elements that could be considered in addressing and preparing for higher direct broadcast data rates. As the feasibility and implications of these elements have not been established, they do not form recommendations, but are presented for further study and evaluation by the agencies.

The CGMS paper “Future direct broadcast data rates from polar orbiting satellites” [CGMS-48-EUMETSAT-WP-15] considers possible technical solutions to increase X band data rate, being:

- Simultaneous use of RHCP and LHCP;
- Coding and Modulation;
- Multi-beam design;
- Improvements to the Direct Broadcast Reception Stations;
- Reduction in Payload Data Rate.

Cost

W4. Owned / dedicated ground equipment leading to higher costs.
Historical lessons show that dependencies on the private sector for access to LEO meteorological satellites data shall be limited, to ensure continuous access to LEO meteorological data that is of paramount importance for NWP predictions.

Reduced dependencies on the private sector justifies higher cost of dedicated ground segment equipment.

W5. Communications links to multiple ground stations required.
Several direct broadcast stations are required to cover large geographical areas. For example, 5 stations are required to cover the European area (see Figure 3).

Commanding

W6. No uplink outside polar regions
Today, commanding of LEO meteorological satellites only occurs at the poles via S-band uplink. Direct broadcast stations do not have a S-band uplink possibilities, limiting the commanding of satellites to the polar regions.

To reduce this weakness, NOAA implemented a commanding functionality of the JPSS satellites series via the geostationary TDRIS system.

W7. Limited monitoring of space assets outside of polar regions
To overcome the limitation of LEO meteorological satellites monitoring to be performed only during the poles, it is a common practice to use Multi-Mission Administrative Messages (MMAM) to transfer satellites related monitoring information via direct broadcast messages. This allows operating agencies to react faster in case and prepare corrective actions before the satellite reaches the pole.

6 OPPORTUNITIES ANALYSIS

GEO Data Relay Service

O1. <u>Global availability of data worldwide through GEO relay constellation.</u> GEO data relay service can provide global low latency data access from a LEO meteorological satellite. The Figure 5 below shows an overview of the GEO data relay service system which consists of:

(A) GEO Relay Space segment;
(B) Ground station as a service from GEO relay operator;
or
(C) Ground station operated by CGMS agency;

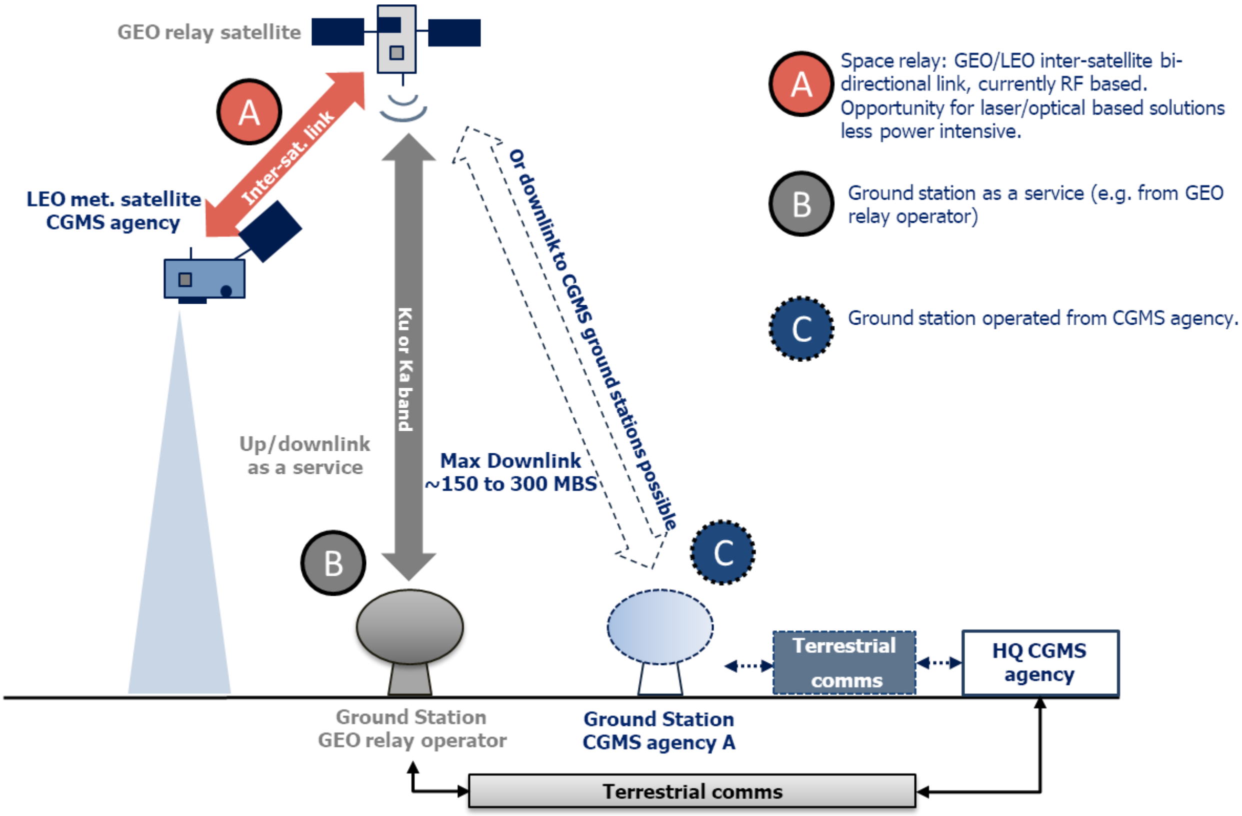

Figure 5: GEO Data Relay Service

The space segment is composed of one or several LEO meteorological satellites and a minimum of 3 GEO relay satellites needed to provide worldwide coverage (see Figure 6). Global coverage would most likely be offered from a set of GEO relay operators depending on the globe location. However some operators already offer a full global coverage service (e.g. Inmarsat Global Xpress).

A series of 3 to 4 GEO relay satellite receives data from the LEO meteorological satellite via an inter-satellite link and repatriates it to a ground station. They are two possible LEO to GEO solutions for this:

i. The GEO global beam satellites (presented below);
ii. GEO equipped with steerable antenna (e.g. as done for NOAA TDRS and EDRS). These need to be scheduled by the transmitting satellites are not designed to take multiple, parallel transmissions. This solution would be

expensive, as only a few satellites could be supported if a RT link is required (rather than transmission of recorded data) when in visibility. Advantage of this solution is support for polar measurements and relatively straightforward to schedule transmissions (equivalent to transmission to a ground station).

Currently, the inter-satellite links between a LEO and GEO using beams are RF based signal. For example, a digital beam formed via a phased array antenna on a LEO satellite would be suitable, although bringing the signal from the LEO meteorological orbit (800 km) to a GEO orbit (36 000 km) would consumes a large amount of on-board power. If inter-satellite links evolve to an optical (laser) base solution, this could help reducing power consumption required for transmitting signal. A bi-directional link offers the possibility of sending data in low latency to the LEO satellite, however this also brings security risk regarding satellite commanding operations.

Each GEO satellite has multiple beams covering specific sections of the terrestrial globe (see Figure 6). At the nadir of the GEO satellite, a LEO satellite would be changing GEO beams in short amount of time (~seconds) which would require a precise on-board LEO software to manage connections changes between beams. In case of loss of a prime GEO relay satellite, redundancy will have to be managed on a beam-by-beam footprint cases.
Upcoming opportunities with GEO relay hosting a large aperture antenna providing a wide beam which would allow to maintain a LEO / GEO connectivity over a longer period of time (LEO satellite would likely remain within the same beam when visible from the GEO satellite).

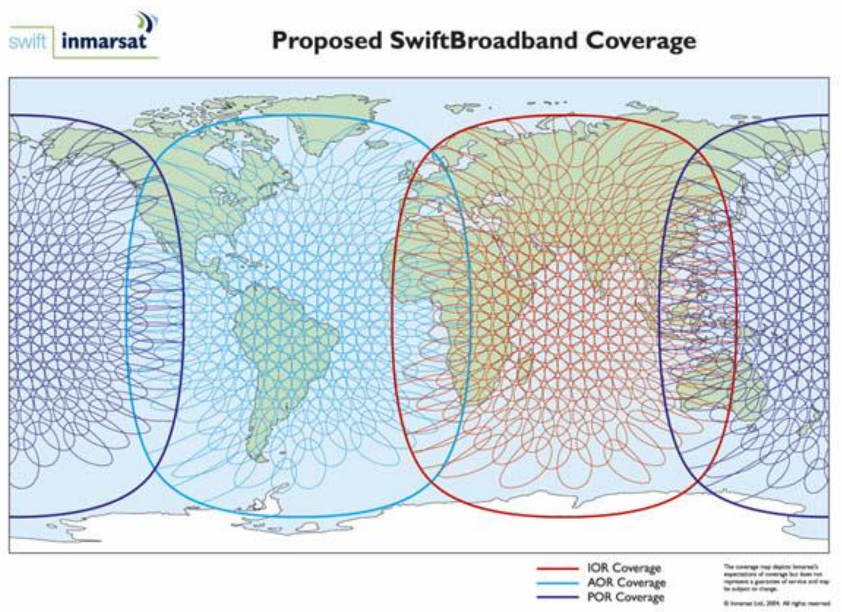

Figure 6: Inmarsat global beams footprints (image credit: Inmarsat)

Some GEO relay satellites also cover the poles if the LEO orbit >500km (e.g. Inmarsat 3 satellites). This would not be the case for all GEO relay satellites which would then mean a potential loss of connection to the LEO satellites at the poles.

The current price of the GEO relay service is approximately 2k/euros/month per Mbps (costing provided by ESTEC). The evolution of the GEO relay service cost is expected to decrease as a result of increased competition on the on GEO relay market as well in the MEO / LEO relay market.

Two options exist for the GEO relay ground segment which are (B) Ground Station as a service, likely from the GEO relay provider or (C) Ground Station operated from the CGMS agency. The purchase of a GEO relay as an end 2 end service, meaning that the GEO operator delivers data as a service, is relatively new on the market but will likely become a common option in the future.

Independently from the choice of operation between (B) and (C), a GEO relay ground segment will be composed of a ground station and a terrestrial communications link with the CGMS agency headquarter.

The downlink from the GEO relay satellite is bi-directional and typically done via RF signal in Ku or Ka band with a data rate per GEO beams of 150 Mbps to 300 Mbps.

O2. <u>Maturing market with Inmarsat, SES Astra and many others</u>

GEO relay service has matured with many offers, see for example:

- Inmarsat GEO relay solution for LEO satellites:
    - https://www.addvaluetech.com/category/connection-to-space/idrs/;
- SES ASTRA partnering with NASA to offer GEO relay for LEO satellites:
    - https://www.ses.com/press-release/nasa-selects-ses-government-solutions-support-near-earth-communications.

LEO Relay Service

O3. <u>Global availability of data worldwide through LEO relay constellation.</u>

This opportunity considers the use of a LEO or MEO data relay constellation to provide global low latency data access from a LEO meteorological satellite.
The Figure 7 below shows an overview of either a LEO or MEO data relay service system which consists of:

(A) LEO/MEO Relay Space Segment;
(B) Ground Station as a service from LEO/MEO relay operator.

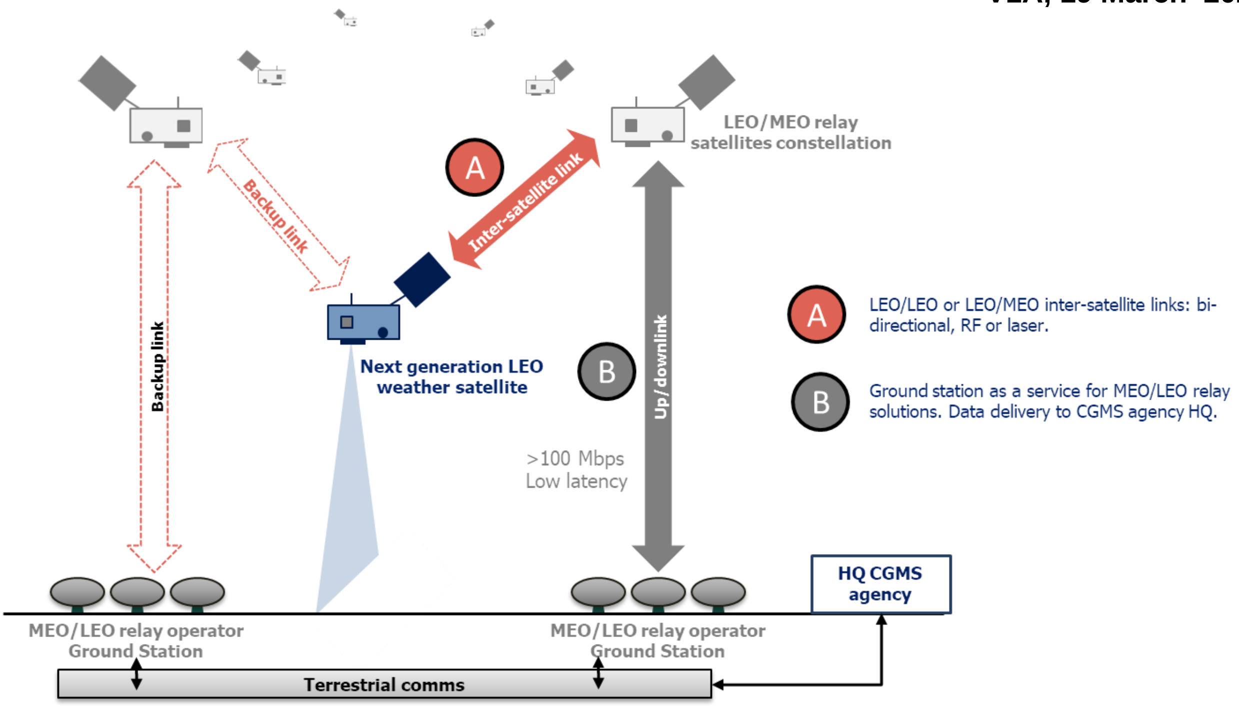

Figure 7: LEO/MEO Data Relay Service

The space segment is composed of at least one LEO meteorological satellite and a LEO/MEO relay constellation. The number of relay satellites could range from a dozen for a MEO constellation (e.g. 11 satellites for O3b SES, see Figure 8) to several thousand for a LEO constellation (12000 satellites for SpaceX Starlink V1 system with option to extend to 42000 for Starlink V2 system).

(a) (b)

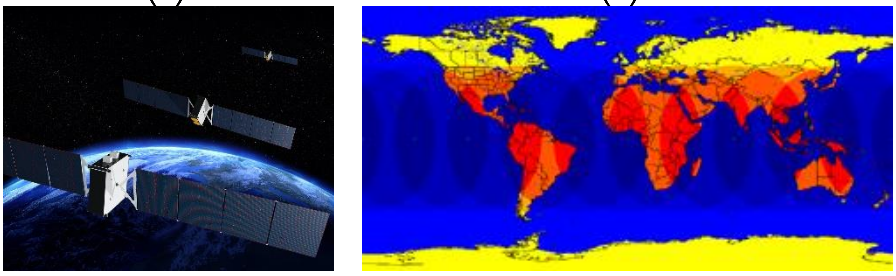

Figure 8: Boeing O3b mPOWER constellation of 11 MEO satellites with (a) artist view of constellation (image credit SES) (b) constellation ground footprint (image credit SES)

(a) (b) (c)

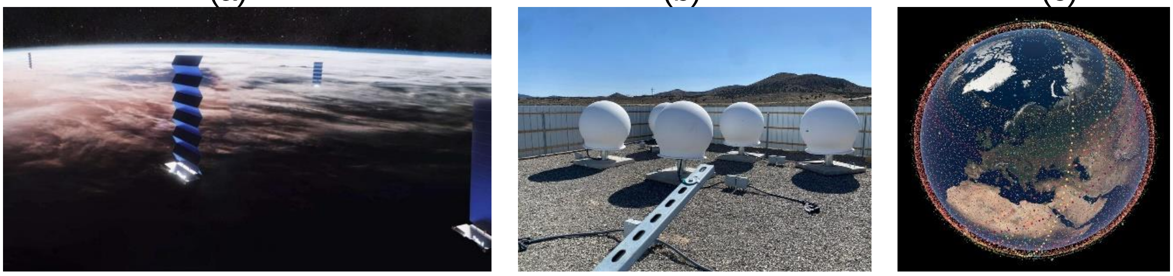

Figure 9: SpaceX Starlink constellation with (a) artist view of constellation (image credit SpaceX) (b) typical Starlink ground station gateway (image credit Reditt) (c) Visualisation of the 30 000 planned satellites from the Starlink Generation 2 constellation as of 2022. Different sub-constellations are illustrated with a different colour (image credit ESO).

Inter-satellite link between LEO/MEO are currently RF based, which is the case for the O3b MEO constellation and Starlink V1.0. However, next generation of Starlink V1.5 and V2.0 satellites will uses laser inter-satellites communication. Laser based communications have the advantages of light weight and lower on-board power consumption but brings a threat of compatibility as they are currently no standards.

Although the cost of a MEO relay constellation is similar to GEO relay, the cost of LEO relay is much lower of about 110 dollar for 50 Mbps per month for a personal Starlink user and 5000 dollar per month for a marine corporate user with higher bandwidth of up to 350 Mbps (https://www.starlink.com/maritime). Therefore, accounting for the price of a corporate Starlink user, brings an indicative price of 15 dollar per Mbps for a LEO relay constellation.

Currently, some LEO constellation, such as Starlink, do not accept space communications from external satellites (e.g. from non-Starlink satellites). It could be that future Starlink satellites will provide an entry connection point for external satellites, although it is not confirmed at this point in time.
For downlink, the Ku and Ka bands are the current standard, which for example used for the MEO and Starlink V1 satellites. However, the V2.0 Starlink satellites will fly in a lower ~350 km orbit and operate in V band.
For MEO and LEO constellations, the ground stations are operated by the relay satellites operator meaning that the data access to/from the LEO meteorological satellite is providing as a service.

O4. Low maturity, many new markets appearances.

Although LEO relay service providers exist (for ground-based users), no offer yet available for LEO to LEO relay data service.

Ground Stations as a Service

O5. Regional availability of data through a global network of ground stations as a service.

This opportunity considers the use of a global network of ground stations as a service to provide global low latency data access from a LEO meteorological satellite.
The Figure 10a below shows an overview of a global ground segment service which consists of:

(A) Space Segment;
(B) Ground station as a service from one or several operators.

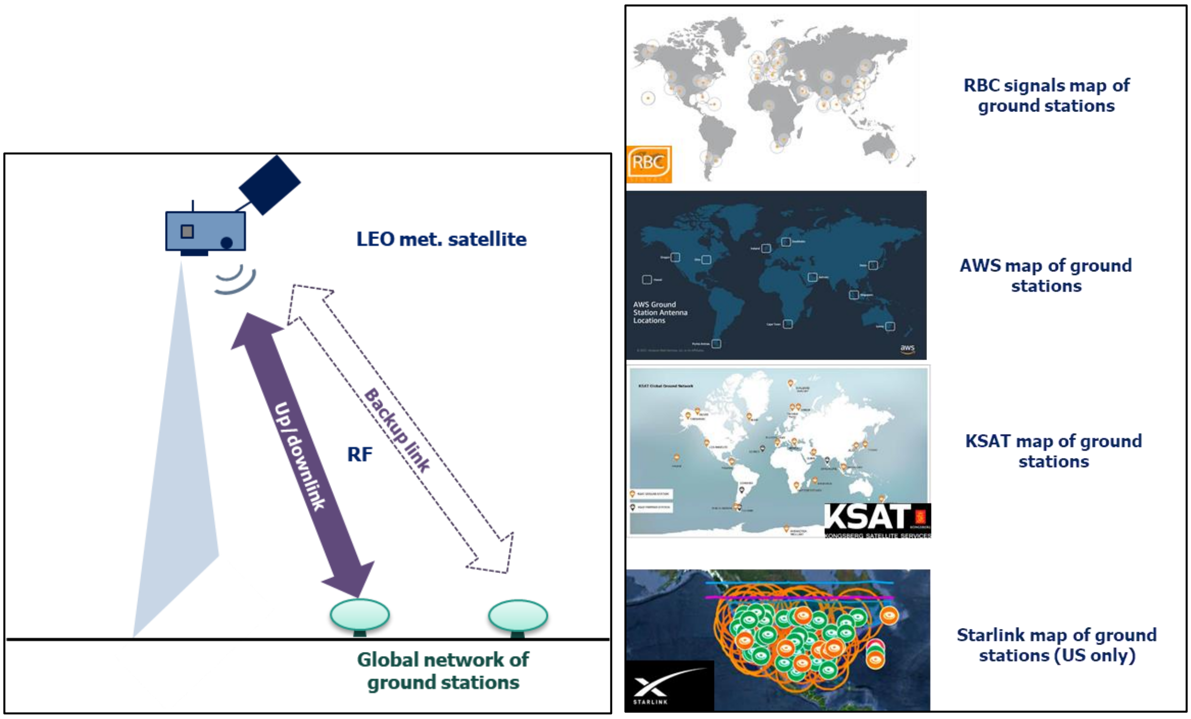

Figure 10: (a) Global Network of Ground Stations (b) Non-exhaustive list of current global network ground stations

O6. High maturity.

The Figure 10b shows a current list of a global network of ground stations providers. Network of traditional tracking antennas are found to be more expensive and sparse than phased array (example of Starlink stations map in the US).

It is expected that the development of global network of phased array stations will grow over the next years as they present advantages to traditional antennas for LEO satellites.

Satellite Platform:

O7. <u>Built-in GEO relay transponder</u>

IQ spacecom offers a lightweight transponder (200 grams) that provides connectivity to the Inmarsat GEO fleet, see Figure 11 below.

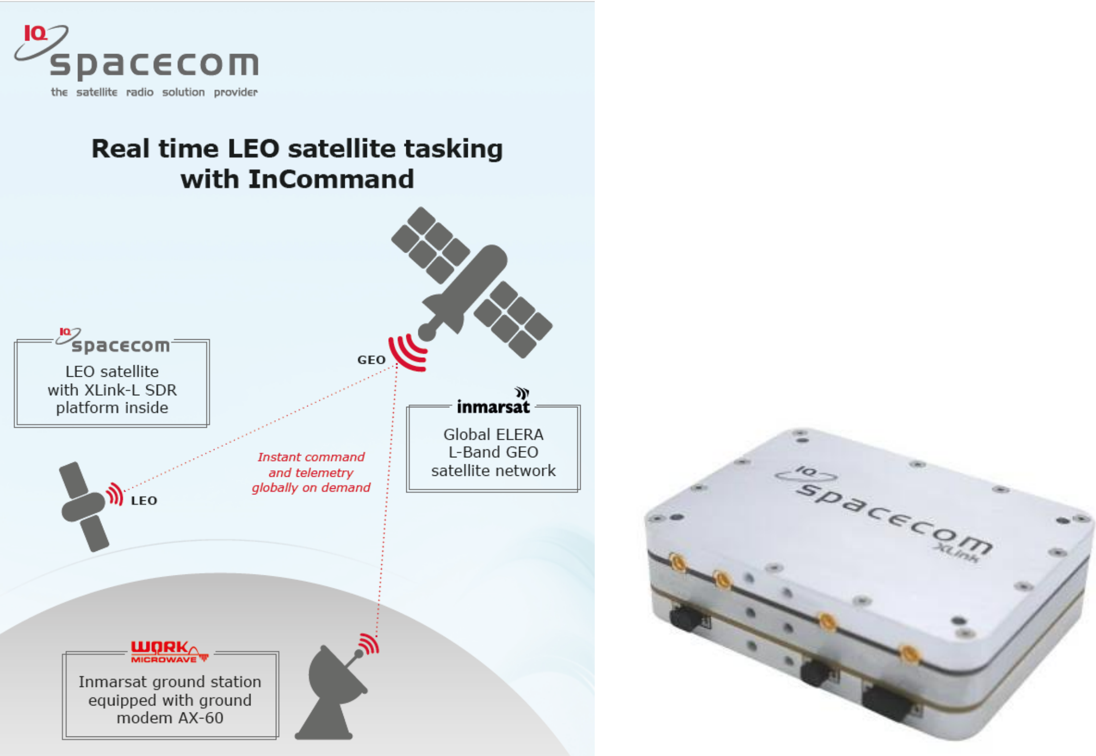

Figure 11: Low cost, lightweight system for instant tasking of small LEO satellites (Inmarsat and IQ spacecom)

O8. <u>Satellite Platform as a Service (SPaaS), covering launch to operations.</u>

Satellite Platform as a Service providers offer the possibility to integrate an instrument on a LEO satellite platform and cover any aspects of the mission from launch to operations. See for example the Loft Orbital Longbow offer on Figure 12, also offering on-board processing capabilities.

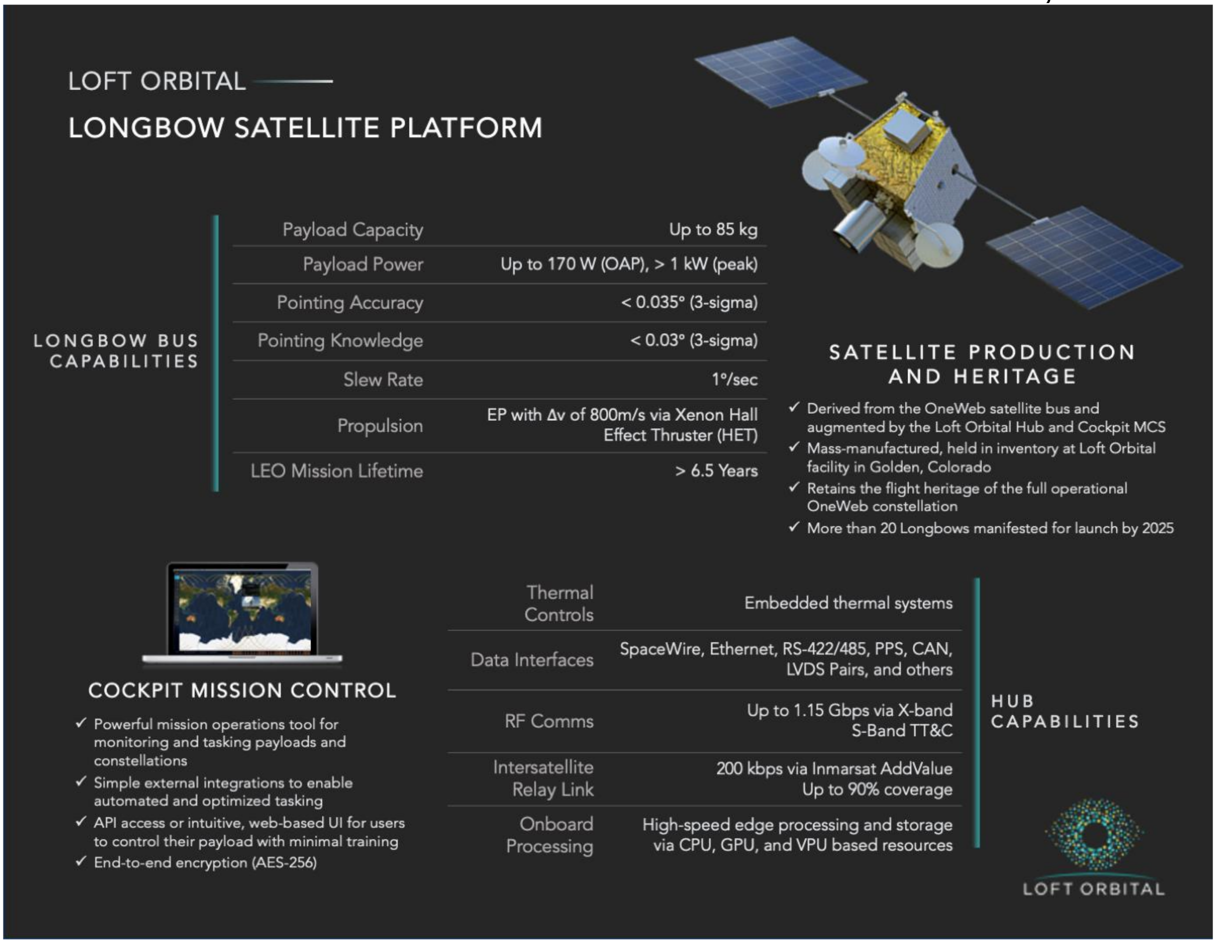

Figure 12: Loft Orbital Satellite Platform

Cloud services:

O9. <u>Complete suite from raw data to products available within most latency requirements.</u>

Cloud service is a mature market with many providers offering processing and dissemination services.

Worth mentioning that Inmarsat offers the most complete package, starting from the LEO to GEO relay transponder (see O7) to direct downlink to Azure cloud (see https://www.inmarsat.com/en/news/latest-news/enterprise/2019/inmarsat-and-microsoft-azure-iot-join-forces-to-deliver-cloud-services-via-satellite.html).

O10. <u>User internet capability will determine volume and latency.</u>

(self-explanatory)

7 THREATS ANALYSIS

Dependence on private sector:

T1. Reliance / dependence on a commercial service for the end2end ownership of data chain

Currently, CGMS agencies retain full ownership of the data transmission chain. There are historical lessons to limit dependence on third parties to secure a timely and systematically access to data. For example, the reception points at the poles to the operating centres of the CMGS agencies have a dedicated terrestrial link to keep ownership of the transmission chain.

T2. Volatile relay satellite operators market

Commercial services have risks, enterprises subject to change (new shareholder, change of group, bankruptcy, etc). Political scenario may also change and impose bans and restrictions on commercial services.

Cost:

T3. Relay constellation bandwidth cost, particularly GEO

Cost of data relay constellation will vary depending on the type of applications between ground-based and space-based (LEO) users, see Table 3.

Table 3: Downlink cost, depending on technology used.

Technology	Cost for ground-based user	Cost for LEO satellite
GEO relay	~1 Mbps for 2 k$/month	~1k$ per Gb/month
LEO relay	~100 Mbps for 100$/month	LEO – LEO offers not available yet
Network of ground stations	N/A	100$/pass (downlink only, e.g. direct broadcast)

It is found that subsidised direct broadcast stations (e.g. DBNET type) offer the best value for money per Gb transmitted for acquiring LEO satellites that have a payload data rate greater than 10 kbps. Assumptions for cost estimates are detailed in Table 4 and Table 5 in Appendix A.

FY3D (35 Mbps), JPSS (15 Mbps), METOP (3500 kbps) and Sterna (67kbps) instrument data rate are all above the 10 kbps threshold, therefore direct broadcast offers the best value for money to repatriate current LEO CGMS payload data.

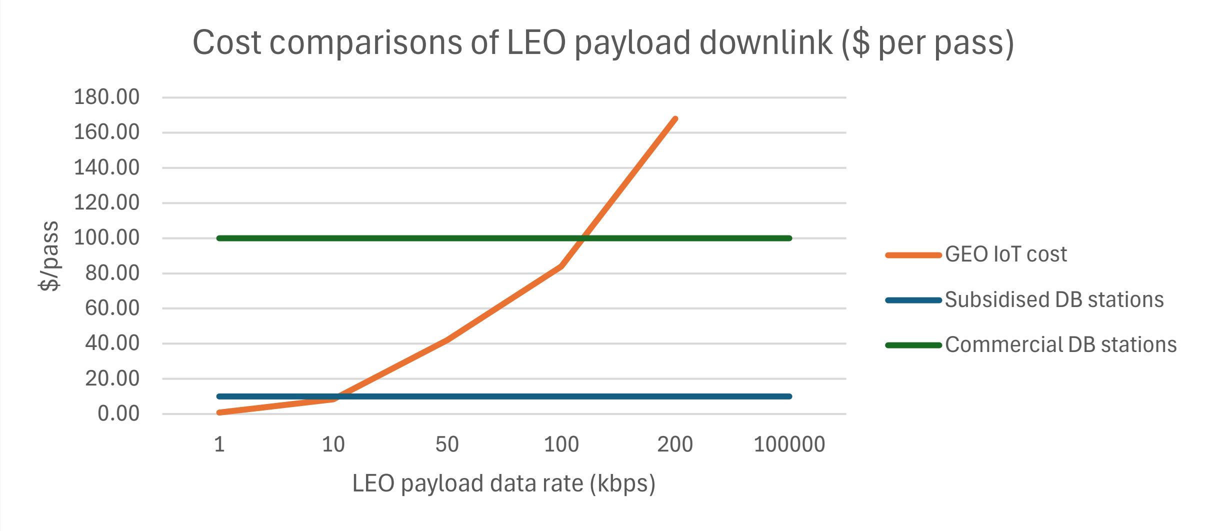

Figure 13: Cost Comparison Analysis of IoT Solutions for LEO Payload Downlink

Frequency protection:

T4. Relay constellation increase pressure on the frequency spectrum

Particular for the case of small/smaller satellite LEO constellations (not relevant for the mentioned cases 03B, Starlink and other such mega constellations) the use of the same frequency bands as used by LEO meteorological satellites are envisaged to downlink the data. This is mainly the case for the MetSat L-Band (1695-1710 MHz) which is and will continued to be used for a direct broadcast to the users, the Earth observation X-Band (8025-8400 MHz) as well as even the S-Band (2200-2290 MHz) downlink, which is of critical importance for the telemetry downlink for LEO meteorological satellite systems. The use of broader bandwidth downlink in S-Band by such small/smaller satellite LEO constellations will accelerate spectrum shortage while other users are trying to limit themselves in their bandwidth use.

Competing with commercial entities for the same very limited frequency resource in the aforementioned bands could in the long-term result in increased level of RFI and even blockage to the access of this spectrum by LEO meteorological satellite systems, fostered by the first-come, first served principle of the ITU-R satellite notification process, where commercial users could strategically use this mechanism to gain advantage over other users.

Security:

T5. For SPaaS Security risk via uplink commands to CGMS satellite.

The provision of internet connectivity to satellite platform via relay constellation is a recent innovation. Resulting security risks for operations of LEO meteorological satellites would require proper analysis.

Coordination & Standards

T6. Role of CGMS inter agency coordination unclear for data exchange mechanism which may change (e.g. via cloud?)

The way users access LEO meteorological data could be impacted by the opportunities identified in this SWOT. Instead of having direct access to the satellite raw data as today, regional users will instead access processed products from a geostationary satellite (EUMETCast type).

Figure 14 provides an overview of access to regional data. The LEO meteorological satellite sends raw data to a relay satellite, that transfers the raw data to a processing centre on the ground, where data is processed to L1/L2 products. This processing centre could be a cloud decentralised platform. The products are then sent to users via a EUMETCast type solution, using a relay satellite as dissemination.

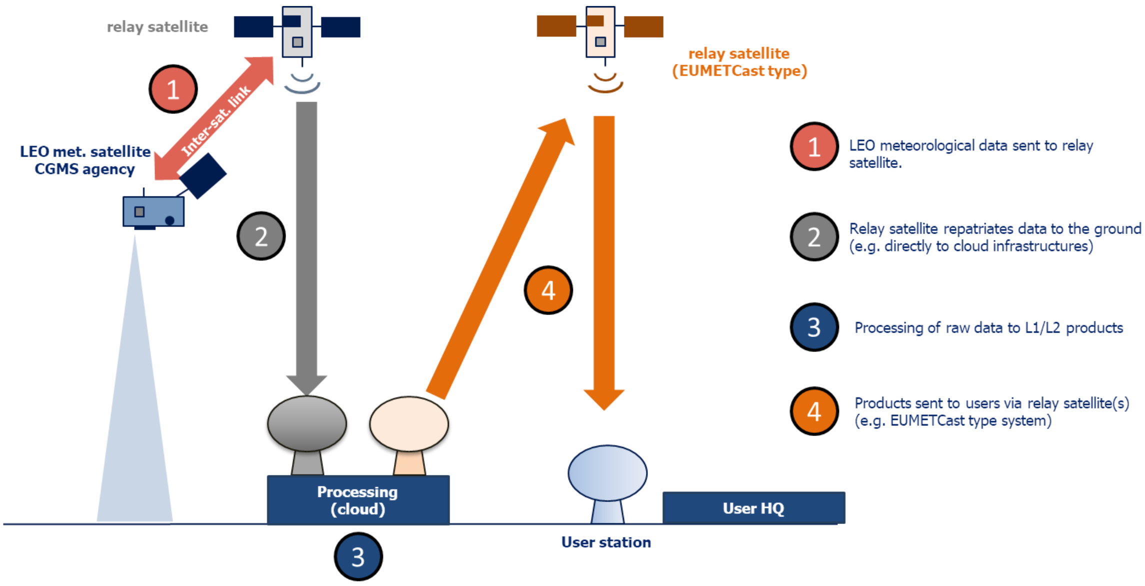

Figure 14: User access to regional data impact

T7. Little to no standards for inter-satellite communications.

Currently, each relay satellite constellation provides its own modem transponder (e.g. see O7). Several transponders are then required to connect to several relay constellations.

8 SWOT CONCLUSION

8.1 Key backbone LEO meteorological constellations (FY3/JPSS/EPS-SG) to keep using direct broadcast, possibly completed by lower cost constellations making use of platform solutions.

Keeping ownership of the access to LEO meteorological is key, allowing full control on the end-to-end data dissemination chain. However, new market opportunities are offering innovative way of low latency data access from LEO meteorological data. A possible outcome from this study could be that future LEO weather satellites systems have a backbone LEO meteorological satellites where the ownership of the data chain is conserved (as for the FY3/JPSS/METOP satellites of today), completed by lower cost LEO satellites constellation, making use of platform hosting solutions.

Timeliness being one critical aspect of a LEO weather satellite for now casting and numerical weather applications, it could be that future LEO weather satellites programmes transition to innovative global low latency data access mechanisms (e.g. GEO relay services). The implications of this transition could result into global services (orbit data reception at the poles) and local services (direct broadcast) to be merged into a single global low latency data service. Requirements for these new types of LEO meteorological satellites would need to be assessed, for example in terms of the space segment architecture, orbit types, orbit coordination, etc.

8.2 GEO IoT to open new mode of operations for LEO meteorological satellites?

Internet on LEO satellite is now a reality with the availability of lightweight (200 grams) GEO transponders as COTS, providing up to 200 kbps internet to LEO satellites. The main associated cost of internet provision to a LEO satellite is charged on the volume of data used.
Live connectivity to the LEO satellite provides the potential to open new mode of operations for LEO meteorological satellites for about 90% orbit coverage, when the LEO satellite is outside of the ground segment coverage.

<u>Telemetry & Telecommand</u>
Telemetry and Telecommand (TM&TC) operations for LEO meteorological satellites are traditionally executed via polar stations. Although TM&TC downlink operations are possible via direct broadcast stations, live connectivity to the LEO satellite provides the potential to perform TM&TC uplink operations outside ground segment coverage such as:

- Direct commands to the spacecraft for reconfiguration;
- Application-specific commands.

With an increasing debris environment in the LEO orbits, it is now routine for CGMS operators to perform ‘collision avoidance manoeuvres’. Live connectivity to the LEO satellite provides via GEO IoT solutions would allow to perform these manoeuvres live, outside ground segment coverage.

Downlink of LEO meteorological satellites instrument payload

This paper identifies three solutions for repatriating LEO meteorological satellite payload in low latency which are GEO IoT and direct broadcast. Direct broadcast acquisition can be achieved via a network of ground stations which are either subsidised.

8.2.1.1 Performance

Timeliness

All solutions offer similar timeliness performance, in terms of reception of raw data to the ground. All timeliness figures between sensing time and acquisition time are within milliseconds.

Coverage

Almost full disk coverage are offered by GEO IoT and DBNET network with some differences. GEO IoT offers full disk coverage except for polar latitudes. DBNET offers disk coverage with exception of oceanic regions and Africa, see Figure 2.

8.2.1.2 Cost

FY3D (35 Mbps), JPSS (15 Mbps), METOP (3500 kbps) and Sterna (67kbps) instrument data rate are all above the 10 kbps threshold (see Figure 13), therefore direct broadcast offers the best value for money to repatriate current LEO CGMS payload data.

APPENDIX A COST COMPARISON ANALYSIS OF IOT SOLUTIONS FOR LEO PAYLOAD DOWNLINK

IOT solutions for LEO payload downlink	Cost assumption	Comment
Direct Broadcast – subsidized station	~$10* per pass	Subsidised cost considering ground station infrastructure already built. Estimate only covering station exploitation and maintenance cost. This cost assumption also assumes a full usage of a reception chain with acquisition of all DBNET satellites (around 1000 passes per month).
Direct Broadcast – commercial station	~$100 per pass	Cost considering a direct broadcast acquisition by commercial ground station. Cost assumption for around 1000 passes per month.
GEO IoT	~$1k per GB per month	Flat rate for GEO IoT solution for LEO payload downlink. Costing estimate does not reflect potential cost reductions with high volume of data.

Table 4: Cost assumptions of IOT solutions for LEO payload downlink

LEO data rate (kbps)	Data volume (Kb/pass)	GEO IoT cost ($/pass)
1	840	0.84
10	8400	8.4
50	42000	42
100	84000	84
200	168000	168
100000	84000000	(not possible, max data rate 200 kbps)

Table 5: GEO IoT cost depending on LEO payload data rate. Data volume based on assumption of 14 minutes pass (840s).