

<p>Subject</p>	<p>Strengths, Weaknesses, Opportunities and Threats (SWOT) Analysis of Low Latency Data Access from LEO Meteorological Satellites</p>
<p>In response to CGMS action/recommendation</p>	<p>WGI/A52.02 Identify concrete CGMS actions based on the LLDA SWOT, including priority areas and demonstration cases in agencies. E.g. cloud, TT&C, relation with private sector, etc.</p>
<p>HLPP reference</p>	<p>2.8 New technologies for satellite systems.</p> <p>2.8.1 Assess the Internet-Of-Things technology for inter- and intra-connections between satellite and ground network.</p> <p>2.8.2 Explore improvements to LEO satellite systems low latency data access from both a global and regional perspective, harnessing common emerging technologies and taking account of the evolution of the commercial and agency space systems.</p>
<p>Executive Summary</p>	<p>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.</p> <p>Today, LEO meteorological satellites have two distinct services for providing low latency data to users:</p> <ul style="list-style-type: none"> • 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. <p>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</p>

	<p>latency data access solutions could help in improving timeliness globally.</p>
<p>Action/Recommendation proposed</p>	<p>WG1 is invited to take note and comment on the SWOT Analysis of Low Latency Data Access from LEO Meteorological Satellites.</p> <p><u>Recommendation 1: No further actions needed regarding action WGI/A52.02</u></p> <p>Opportunities on commercial sector are covered by:</p> <ul style="list-style-type: none"> • CGMS best practice document published for relationship with the private sector for commercial data purchases [EUM/CGMS/DOC/24/1408350]; • Task group “Satellite data and code” in WGI manages commercial data format; • WGIV manages dissemination of commercial LEO weather. <p>Opportunities on GEO and LEO data relay services are captured in:</p> <ul style="list-style-type: none"> • Future Information Technologies - Internet-of-Things CGMS-52-WGI-WP-06. <p>Cloud opportunities are covered by:</p> <ul style="list-style-type: none"> • WGIV scope (Cloud services interoperability CGMS-53-WGIV-WP-04). <p><u>Action: Enhance SWOT analysis for CGMS-55:</u></p> <ul style="list-style-type: none"> • Report on feasibility and applications of phased array; • Identify artificial intelligence applications opportunities within scope of LLDA task group, in coordination with WGII.

Table of Contents

1	CONTEXT AND SCOPE	5
2	SWOT ANALYSIS SUMMARY TABLE	7
3	STRENGTHS ANALYSIS	9
	Maturity.....	9
	S1. Well established LEO weather space segment:.....	9
	S2. Well established ground segment worldwide for regional and global missions:...	10
	S3. Well established coordination at CGMS, DBNET / WMO levels.	11
	S4. Well established standards and best practices	11
	S5. Well established data distribution mechanisms to users.....	12
	End2End ownership of data chain.....	12
	S6. Owned assets:.....	12
4	WEAKNESSES ANALYSIS	14
	Downlink and Latency	14
	W1. High latency over regions without direct broadcast, e.g. gap over oceanic regions	14
	W2. Duplicated products between regional and global products	15
	W3. Data rate limitation in direct broadcast X band.....	15
	Cost 1516	
	W4. Owned / dedicated ground equipment leading to higher costs.....	1516
	W5. Communications links to multiple ground stations required.	16
	Commanding	16
	W6. No uplink outside polar regions	16
	W7. Limited monitoring of space assets outside of polar regions.....	16
5	OPPORTUNITIES ANALYSIS	1617
	Commercial Weather Data	1617
	O1. Commercial weather data from LEO satellites.	1617
	Satellite Data Relay Service	1718
	O2. GEO relay constellation.....	1718
	O3. LEO relay constellation.....	2021
	Ground Stations as a Service.....	2324

O4.	Regional availability of data through a global network of ground stations as a service.	<u>2324</u>
	Cloud services:	<u>2425</u>
O4.	Cloud service offering processing and dissemination within most latency requirements.	<u>2425</u>
	Satellite Platform:	<u>2627</u>
O5.	Satellite Platform as a Service (SPaaS), covering launch to operations.	<u>2627</u>
6	THREATS ANALYSIS	<u>2829</u>
	Dependence on private sector:.....	<u>2829</u>
T1.	Reliance / dependence on a commercial service for the end2end ownership of data chain	<u>2829</u>
T2.	Volatile relay satellite operators market.....	<u>2829</u>
	Cost: <u>2930</u>	
T3.	Relay constellation bandwidth cost, particularly GEO	<u>2930</u>
	Frequency protection:.....	<u>3034</u>
T4.	Relay constellation increase pressure on the frequency spectrum	<u>3034</u>
	Security:.....	<u>3132</u>
T5.	For SPaaS Security risk via uplink commands to CGMS satellite.....	<u>3132</u>
	Coordination & Standards	<u>3132</u>
T6.	Role of CGMS inter agency coordination unclear for data exchange mechanism which may change (e.g. commercial)	<u>3132</u>
T7.	Standards needed for inter-satellite communications.....	<u>3132</u>
7	SWOT CONCLUSION	<u>3233</u>
7.1	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.	<u>3233</u>
7.2	IoT to open new mode of operations for LEO meteorological satellites?.....	<u>3233</u>
7.2.1	Telemetry & Telecommand	<u>3234</u>
7.2.2	Downlink of LEO meteorological satellites instrument payload	<u>3334</u>
APPENDIX A	COST COMPARISON ANALYSIS OF IOT SOLUTIONS FOR LEO PAYLOAD	
DOWNLINK	<u>3435</u>	
APPENDIX B	NEON FACT-SHEET	<u>3637</u>

Table of Figures

Figure 1: Current direct broadcast data downlink solution considered for SWOT analysis	5
Figure 2: DBNet-ATOVS coverage in 2025	11
Figure 3: EUMETSAT owned ground segment assets: Svalbard ground station for global mission (left), EARS stations for direct broadcast acquisition (right)	13
Figure 4: NOAA direct broadcast reception network	14
Figure 5: GEO Data Relay Service	18
Figure 6: Inmarsat global beams footprints (image credit: Inmarsat)	<u>1920</u>
Figure 7: LEO/MEO Data Relay Service	21
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)	<u>2223</u>
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)	<u>2223</u>
Figure 10: Loft Orbital Satellite Platform	<u>2728</u>
Figure 11: Low cost, lightweight system for instant tasking of small LEO satellites (Inmarsat and IQ spacecom)	<u>2829</u>
Figure 12: Cost Comparison Analysis of IoT Solutions for LEO Payload Downlink	<u>3034</u>

Table of Tables

Table 1: Confirmed Direct Broadcast Agenda for CGMS agencies	6
Table 2: History of LEO meteorological satellites from CGMS agencies with Direct Broadcast	10
Table 3: Commercial Radio Occultations Providers	17
Table 4: Non-exhaustive list of ground stations as a service providers	<u>2324</u>
Table 5: Examples of cloud usage in CMA	<u>2425</u>
Table 6: Examples of cloud usage in EUMETSAT	<u>2526</u>
Table 7: Examples of cloud usage in JAXA	<u>2526</u>
Table 8: Examples of cloud usage in NOAA	<u>2627</u>
Table 9: Downlink cost, depending on technology used.	<u>2930</u>
Table 10: Cost assumptions of IOT solutions for LEO payload downlink	<u>3435</u>

Table 11: GEO IoT cost depending on LEO payload data rate. Data volume based on assumption of
14 minutes pass (840s).....~~3536~~

1 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.

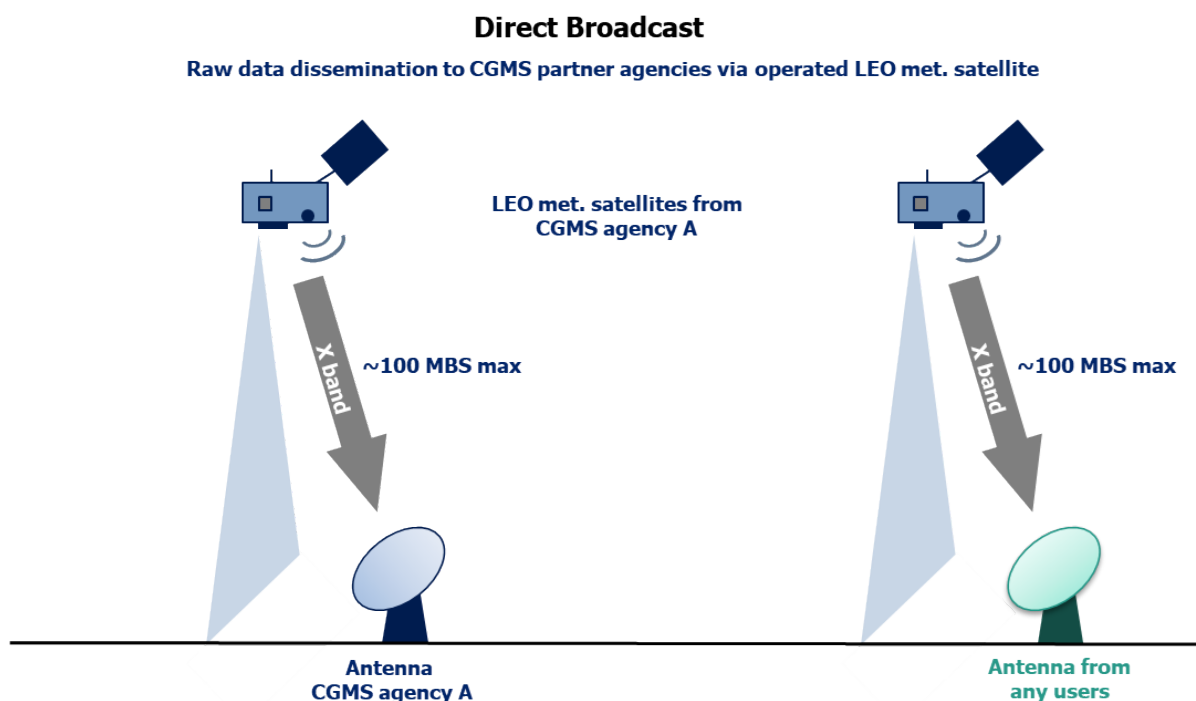


Figure 1: Current direct broadcast data downlink solution considered for SWOT analysis

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](#)).

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-3I, J	2026 - 2027	~2034
NOAA	JPSS2, 3 and 4	2022 – 2038	~2043
EUMETSAT	EPS-SG	2025 – 2037	~2042
	EPS-Sterna	2029 – late 2030s	~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 2: SWOT Analysis Summary Table;
- Section 3: Strengths;
- Section 4: Weaknesses;
- Section 5: Opportunities;
- Section 6: Threats;
- Section 7: SWOT Conclusion.

2 SWOT ANALYSIS SUMMARY TABLE

<p style="text-align: center;">S</p> <p style="text-align: center;">Strengths</p>	<p style="text-align: center;">W</p> <p style="text-align: center;">Weaknesses</p>	<p style="text-align: center;">O</p> <p style="text-align: center;">Opportunities</p>	<p style="text-align: center;">T</p> <p style="text-align: center;">Threats</p>
<p><u>Maturity:</u></p> <p>S1. Well established LEO weather space segment</p> <p>S2. Well established ground segment worldwide for local and global missions</p> <p>S3. Well established coordination at CGMS, DBNET and WMO levels.</p> <p>S4. Well established standards and best practices</p> <p>S5. Well established data distribution mechanisms to users</p> <p><u>End2End ownership of data chain:</u></p> <p>S6. Owned space and ground equipment, giving more control over assets. Limited reliance on private sector in the data chain.</p>	<p><u>Downlink and Latency:</u></p> <p>W1.High latency over regions without direct broadcast, e.g. gap over oceanic regions</p> <p>W2.Duplicated products between regional and global products</p> <p>W3.Data rate limitation in direct broadcast X band</p> <p><u>Cost:</u></p> <p>W4.Owned / dedicated ground equipment leading to higher costs.</p> <p>W5.Communications links to multiple ground stations required.</p> <p><u>Commanding:</u></p> <p>W6.No uplink outside polar regions</p>	<p><u>Commercial weather data:</u></p> <p>O1. Commercial weather data from LEO satellites.</p> <p><u>Satellite data relay services:</u></p> <p>O2. GEO relay services.</p> <p>O3. LEO relay services.</p> <p><u>Ground stations as a Service:</u></p> <p>O4. Regional availability of data through a global network of ground stations as a service.</p> <p><u>Cloud services:</u></p> <p>O5. Cloud service offering processing and dissemination within most latency requirements.</p>	<p><u>Dependence on private sector:</u></p> <p>T1. Reliance / dependence on a commercial service for the end2end ownership of data chain</p> <p>T2. Volatile relay satellite operators market</p> <p><u>Cost:</u></p> <p>T3. Relay constellation bandwidth cost, particularly GEO</p> <p><u>Frequency protection:</u></p> <p>T4. Relay constellation increase pressure on the frequency spectrum</p> <p><u>Security:</u></p>

	W7. Limited monitoring of space assets outside of polar regions	Satellite Platform: O6. Satellite Platform as a Service (SPaaS), covering launch to operations.	T5. SPaaS and relay satellites: Increased security risks with commanding access to satellite. Coordination & Standards: T6. Role of CGMS inter agency coordination unclear for data exchange mechanism which may change (e.g. commercial) T7. Standards needed for inter-satellite communications.
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3 STRENGTHS ANALYSIS

Maturity

3.1 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)	Metop-A (2006)	NOAA-1 (1970)
FY-3B (2010)	Metop-B (2012)	NOAA-2 (1972)
FY-3C (2013)	Metop-C (2018)	NOAA-3 (1973)
FY-3D (2017)		NOAA-4 (1974)
FY-3E (2021)		NOAA-5 (1976)
FY-3G (2023)		NOAA-6 (1979)
FY-3F (2023)		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)
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Table 2: History of LEO meteorological satellites from CGMS agencies with Direct Broadcast

S1. 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:

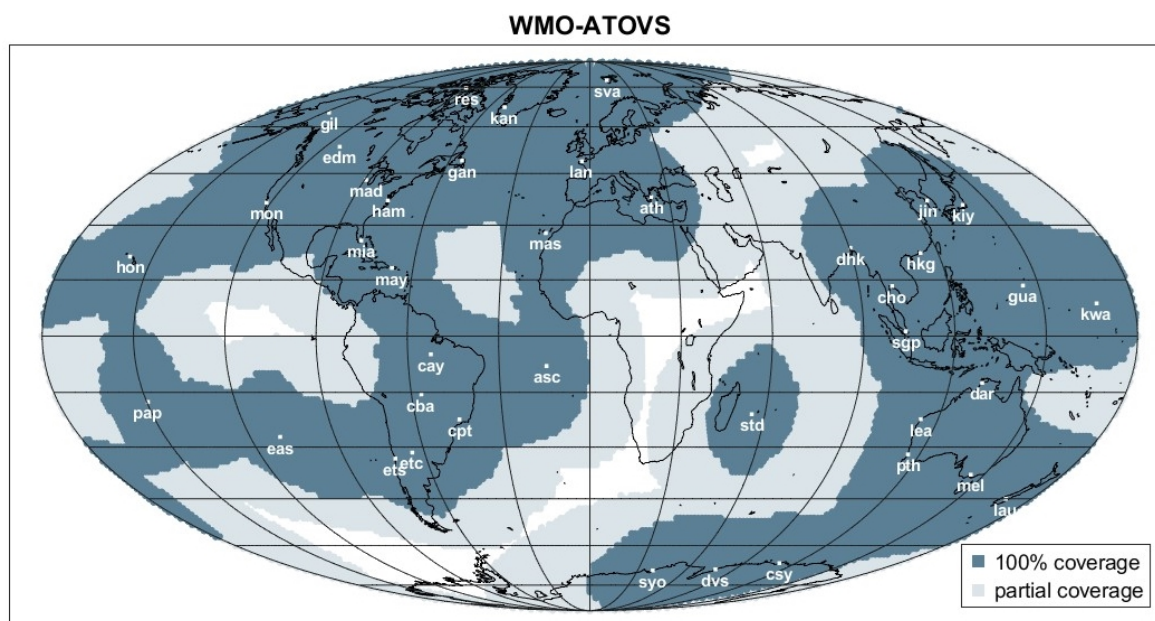


Figure 2: DBNet-ATOVS coverage in 2025

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

S2. 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>

S3. 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].

S4. 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

S5. 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.

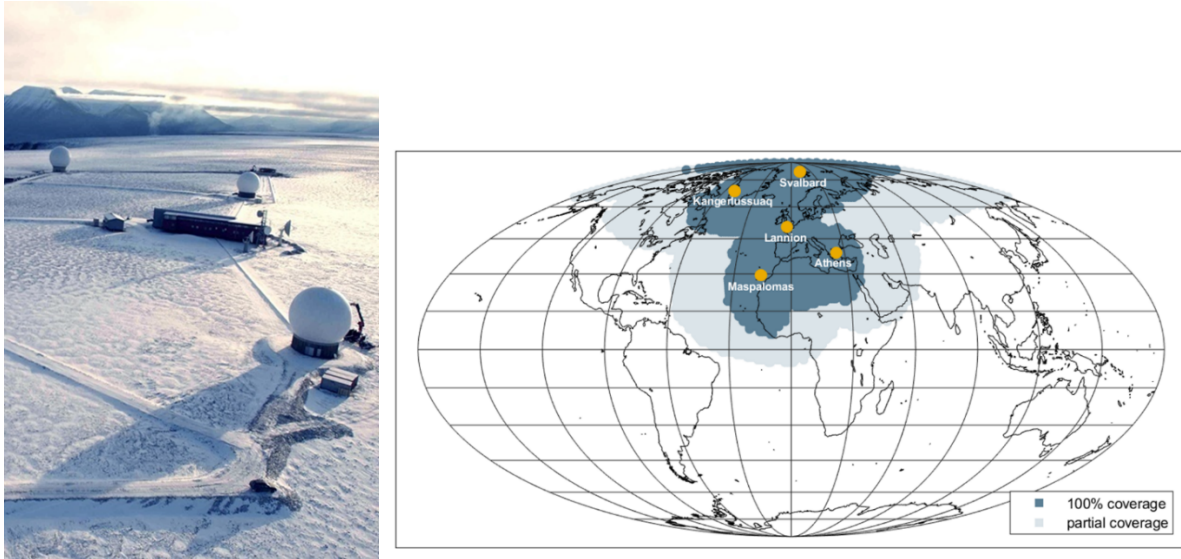


Figure 3: EUMETSAT owned ground segment assets: Svalbard ground station for global mission (left), EARS stations for direct broadcast acquisition (right)

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.

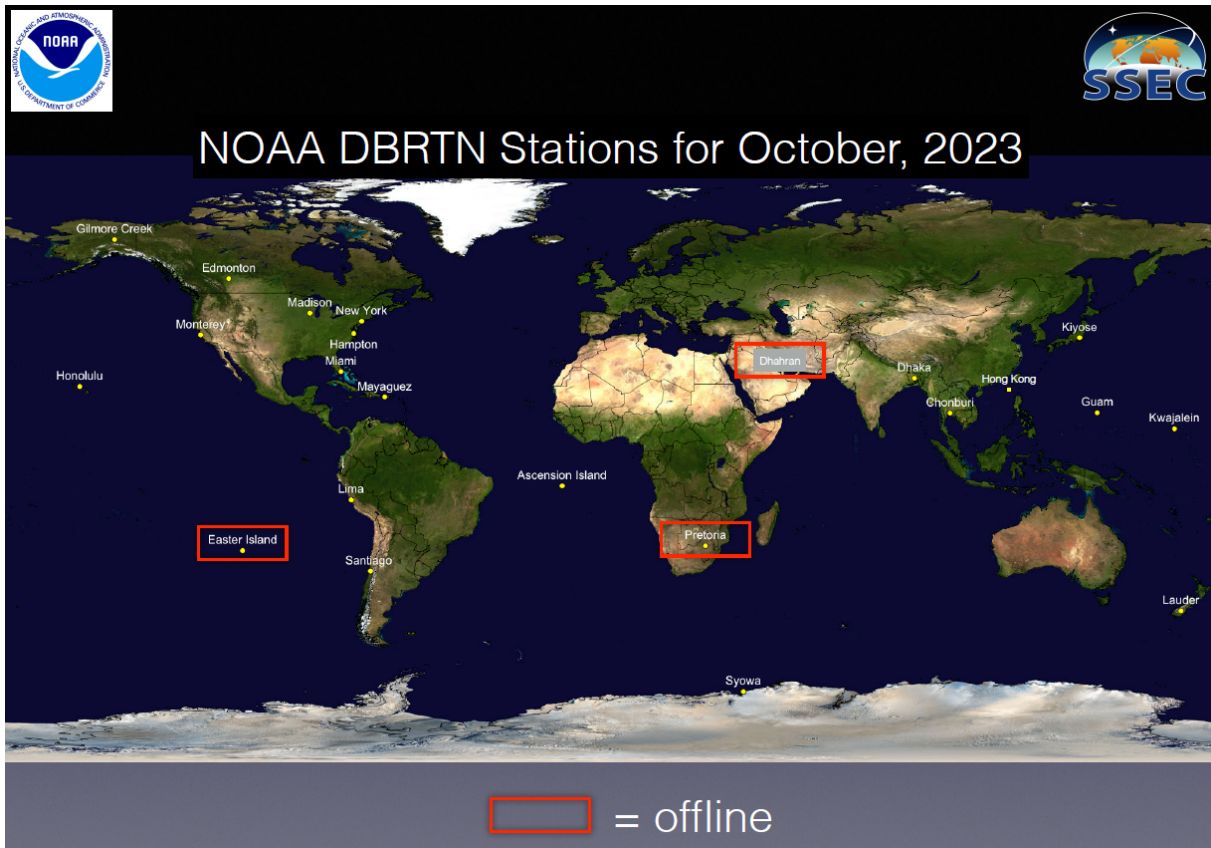


Figure 4: NOAA direct broadcast reception network

4 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.

5 OPPORTUNITIES ANALYSIS

Commercial Weather Data

O1. Commercial weather data from LEO satellites.

Commercial Radio Occultation:

Table 3 summarises the main commercial radio occultations providers. Spire Global provides commercial radio occultations data to NOAA and EUMETSAT.

Table 3: Commercial Radio Occultations Providers

Company	Country / Base	Number of Satellites (approx.)	RO Profiles / Day (approx.)	Notes / Customers
Spire Global	USA	~110+ total CubeSats in constellation	~20,000 (total global production) NASA Technical Reports Server	Largest commercial RO fleet; data used by NOAA, NASA, EUMETSAT
PlanetIQ (GNOMES)	USA	~5 operational with plans for ~20 total (GNOMES constellation)	~3,000–5,000+ from current satellites; ~50,000 target at full 20-sat constellation	Growing RO constellation; NOAA Commercial Data Program customer
GeoOptics (CICERO)	USA / Monaco	~8–24+ CubeSats in CICERO & CICERO-2 constellation (varies over time)	Hundreds per day (e.g., ~500–1,000+)	Early commercial RO provider; data delivered to NOAA and research customers.

NOAA is developing a next-generation microwave atmospheric sounder program “Sounder for Microwave-Based Applications” (SMBA) for its [Near Earth Orbit Network \(NEON\)](#). The Phase-A study of this program focuses on definition and design development of the SMBA instrument under a 12-month contract managed by NASA on NOAA’s behalf. See NEON Fact-sheet in Appendix B for further details.

Satellite Data Relay Service

02. GEO relay constellation.

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.

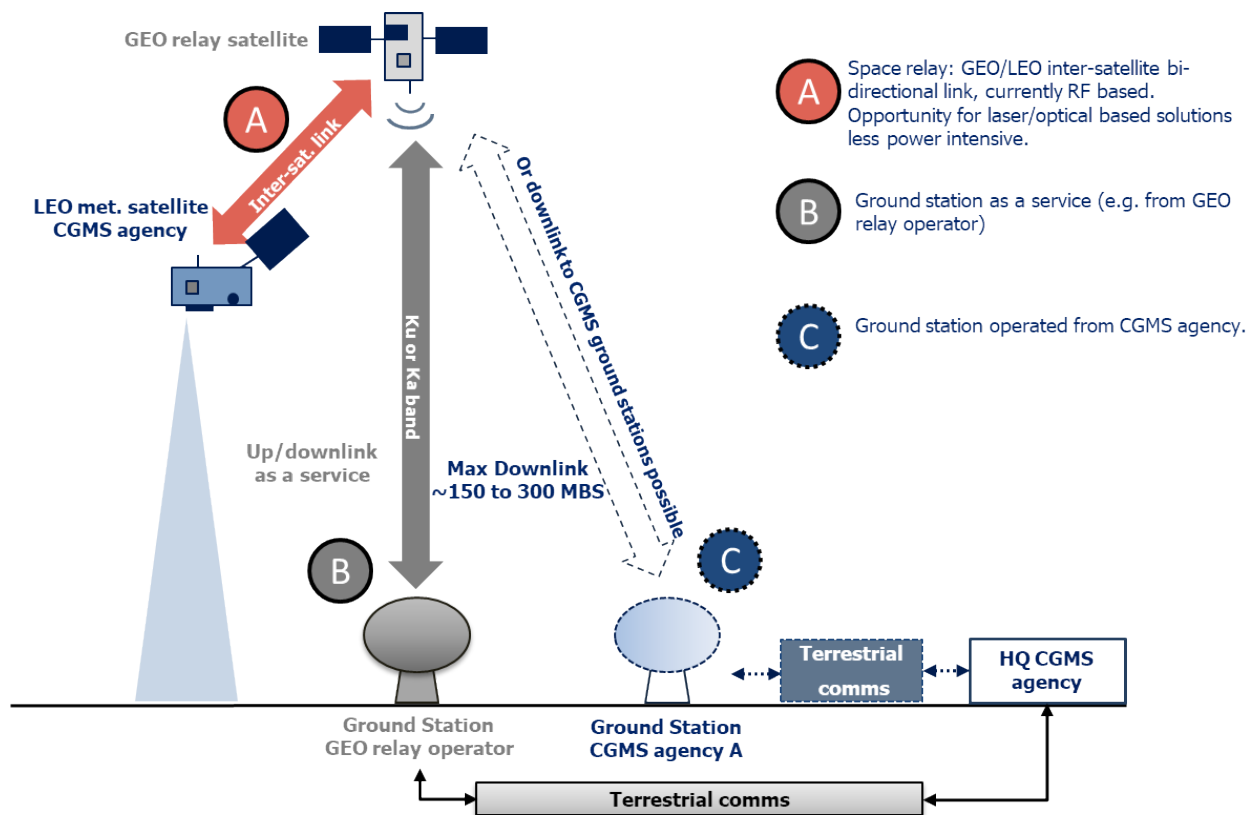


Figure 5: GEO Data Relay Service

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 consume a large amount of on-board power. If inter-satellite links evolve to an optical (laser) based 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).

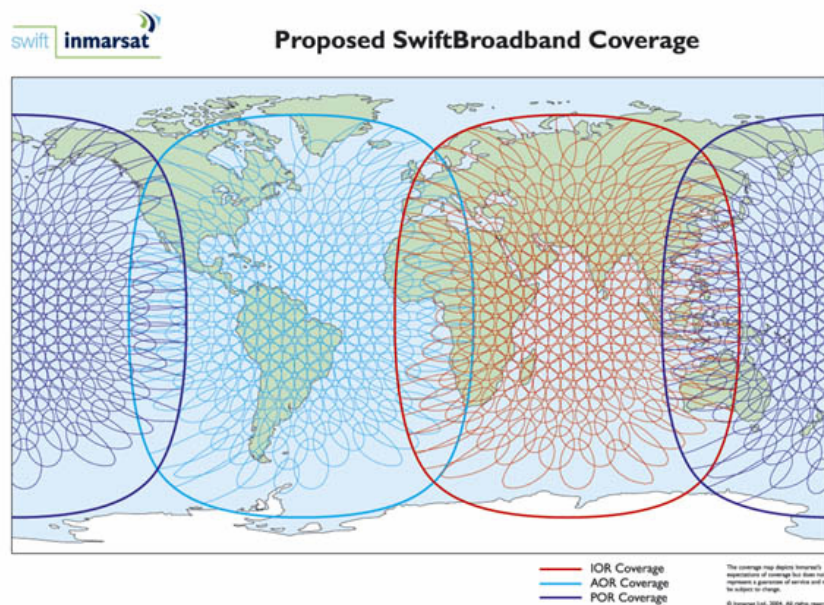


Figure 6: Inmarsat global beams footprints (image credit: Inmarsat)

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.

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>.

03. LEO relay constellation.

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.

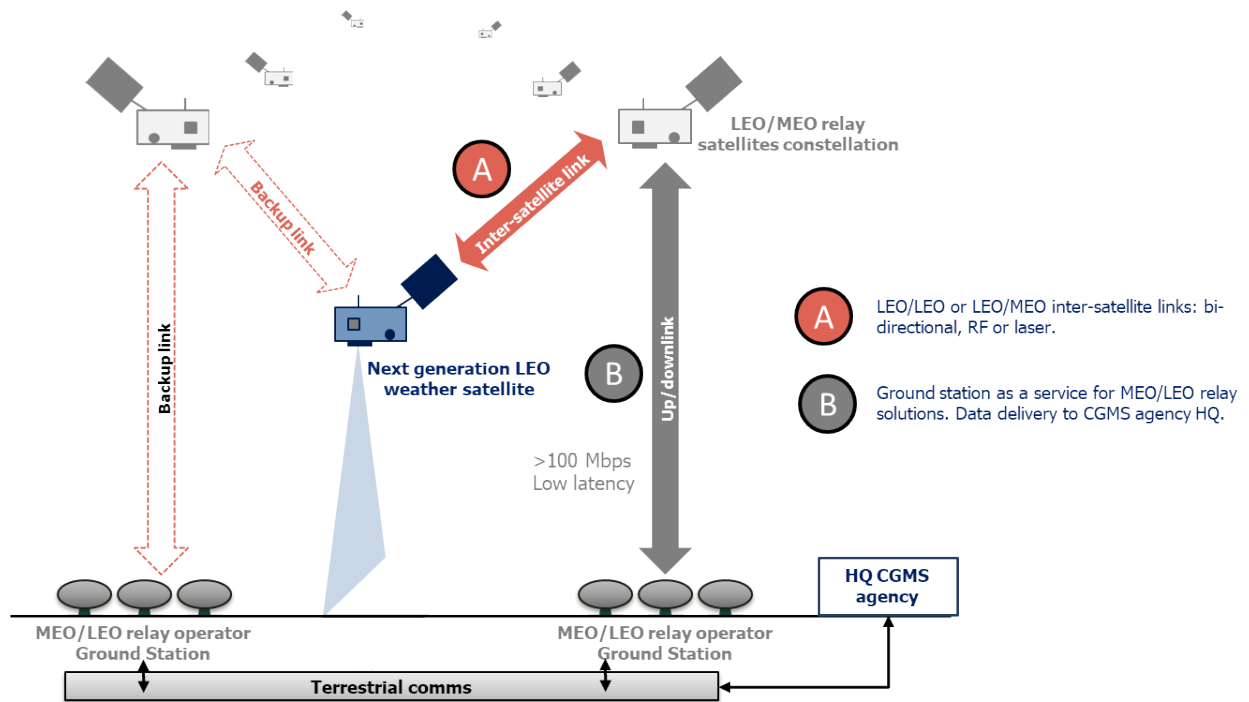


Figure 7: LEO/MEO Data Relay Service

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).

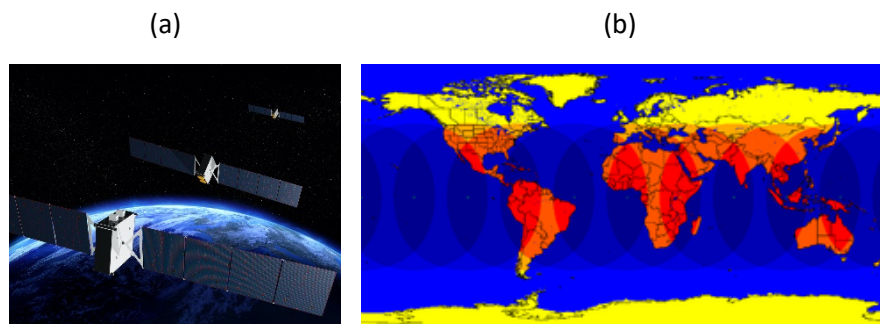


Figure 8: Boeing O3b mPOWER constellation of 11 MEO satellites with (a) artist view of constellation (image credit SES) (b) constellation ground footprint (image credit SES)

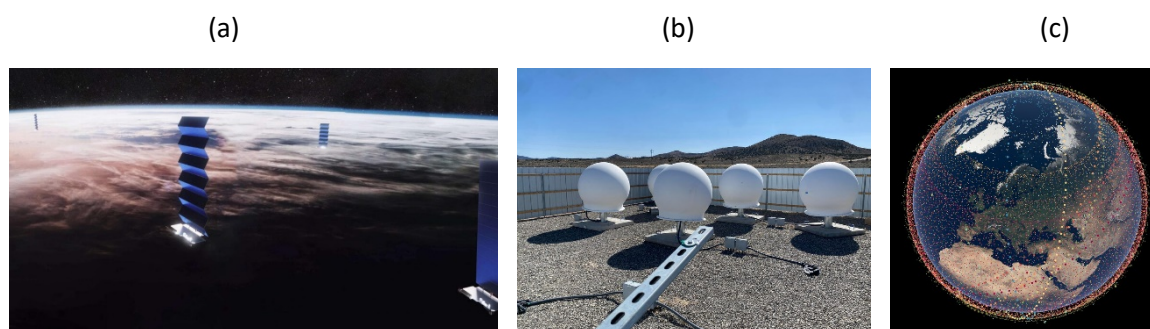


Figure 9: SpaceX Starlink constellation with (a) artist view of constellation (image credit SpaceX) (b) typical Starlink ground station gateway (image credit Reditt) (c) Visualisation of the 30 000 planned satellites from the Starlink Generation 2 constellation as of 2022. Different sub-constellations 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 use laser inter-satellite communication. Laser-based communications have the advantages of light weight and lower on-board power consumption but bring a threat of compatibility as there 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.

Starlink isn't currently offering broad LEO relay to other satellite operators, but they are developing technologies (like laser links) for internal constellation use and exploring "Space User" concepts to potentially support Earth Observation (EO) satellites, treating them as network users.

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.

Ground Stations as a Service

O4. 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. It is expected that the development of global network of phased array stations will grow over the next years.

Table 4: Non-exhaustive list of ground stations as a service providers

Company	Estimated Number of Antennas	Geographic Reach	Core Focus
KSAT (Kongsberg)	300+ Antennas	28+ Global Locations	Largest global footprint; dominant in polar regions.
EQT (formerly Eutelsat)	~1,400 Antennas	100+ Global Locations	Primarily heritage GEO/OneWeb support, now pivoting to commercial GSaaS.
ATLAS Space Ops	50+ Antennas	34+ Global Locations	Federated network; focus on rapid data delivery (<60s latency).
Leaf Space	40+ Antennas	16+ Global Locations	Agile SmallSat support with automated, API-driven scheduling.
SSC (Swedish Space Corp)	~35+ Core Antennas	10+ Primary Sites	High-latitude specialists; second largest commercial network at Espace.
AWS Ground Station	12 - 15 Locations	Global (AWS Regions)	Integrated directly with AWS Cloud; typically 2-3 antennas per region.

Phased array:

NOAA has partnered with KSAT and technology provider ThinkKom Solutions to test phased array antennas. The project specifically evaluates ThinkKom’s VICTS technology, a system capable of tracking and downlinking data from multiple Low Earth Orbit (LEO) satellites simultaneously using Ka-band frequencies. While initial validation has taken place in the US, the technology is specifically designed to meet the high-volume demands of KSAT’s Svalbard Satellite Station (SvalSat). Located in the high Arctic, this station sees every polar orbit, and the phased array system offers the possibility to test high volume of acquisitions in harsh weather conditions. Test report expected to be available mid-2026 from NOAA.

Cloud services:

O4. Cloud service offering processing and dissemination within most latency requirements.

Cloud service is a mature market with many providers offering processing and dissemination services. Table 5, Table 6, Table 7 and Table 8 summarises usage of cloud services in CGMS agencies.

Table 5: Examples of cloud usage in CMA

Category	Cloud Provider(s)	Use Case & Project
National Operations	Tianqing (Internal Private Cloud)	CMADaaS: Centralized "Data as a Service" for all 31 Chinese provinces.
AI & Space Weather	Huawei Cloud	Fengyu Model: AI forecasting for ionospheric and geomagnetic storms.
Public Services	Alibaba Cloud / Huafeng	"China Weather" App: Public-facing mobile and web weather services.
Global Outreach	MAZU Platform (Cloud-Native)	Early Warning for All: Providing AI "Toolboxes" to other countries.

Table 6: Examples of cloud usage in EUMETSAT

Category	Cloud Provider(s)	Use Case & Project
Operational Meteorology	European Weather Cloud (EUMETSAT & ECMWF Private Cloud)	European Weather Cloud (EWC): A specialized cloud for National Met Services (DWD, Météo-France, etc.).
Environmental Monitoring	CloudFerro	WEkEO: The gateway for all Copernicus Sentinel data.
User Access & API	Internal Cloud (EUMETSAT Private Cloud)	Data Store & Data Tailor: API-driven search and cloud-based image cropping/re-projection.
Digital Twin Earth	EuroHPC & T-Systems	Destination Earth (DestinE): Creating a "Data Lake" for high-resolution planet simulations.

Table 7: Examples of cloud usage in JAXA

Category	Cloud Provider(s)	Use Case & Project
Cloud-Native Data Service (API)	F5 Networks SARL	JAXA Earth API https://data.earth.jaxa.jp/en/ JAXA Earth API enables developers and researchers to use JAXA's multiple satellite data easily in programming environment such as Python and JavaScript.
Integrated Data Platform	SAKURA Internet	Tellus https://www.tellusxdp.com/en-us/catalog/data/ Japanese data platform that collects various data including JAXA satellite data such as ALOS and GCOM-C.

Table 8: Examples of cloud usage in NOAA

Category	Cloud Provider(s)	Use Case & Project
Public Data Access	AWS, Google Cloud, Azure	NODD (Open Data Dissemination): Hosting petabytes of satellite (GOES-R) and radar (NEXRAD) data.
Weather Operations	AWS	AWIPS in the Cloud: Moving the forecaster's workstation software to a virtual cloud environment.
High-Performance Computing (HPC)	Microsoft Azure, AWS	Project EAGLE & HAFS: Running experimental hurricane and global weather models in parallel.
Artificial Intelligence (AI)	Google Cloud	Precipitation Nowcasting: Using ML to predict rainfall at 1km resolution within a 6-hour window.
Satellite Data Ingest	AWS	NESDIS Cloud: Direct ingestion of real-time data from polar-orbiting and geostationary satellites.

Inmarsat offers a complete package, starting from the LEO to GEO relay transponder 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>).

User internet capability will determine volume and latency.

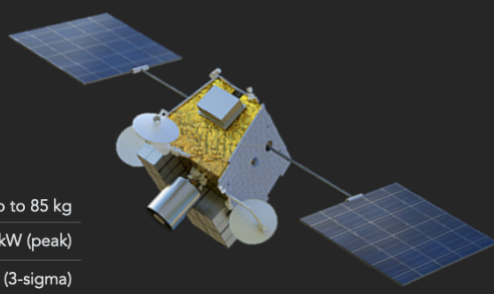
Satellite Platform:

05. Satellite Platform as a Service (SPaaS), covering launch to operations.

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 10, also offering on-board processing capabilities.


LOFT ORBITAL LONGBOW SATELLITE PLATFORM

Payload Capacity	Up to 85 kg
Payload Power	Up to 170 W (OAP), > 1 kW (peak)
Pointing Accuracy	< 0.035° (3-sigma)
Pointing Knowledge	< 0.03° (3-sigma)
Slew Rate	1°/sec
Propulsion	EP with Δv of 800m/s via Xenon Hall Effect Thruster (HET)
LEO Mission Lifetime	> 6.5 Years



SATELLITE PRODUCTION AND HERITAGE

- ✓ Derived from the OneWeb satellite bus and augmented by the Loft Orbital Hub and Cockpit MCS
- ✓ Mass-manufactured, held in inventory at Loft Orbital facility in Golden, Colorado
- ✓ Retains the flight heritage of the full operational OneWeb constellation
- ✓ More than 20 Longbows manifested for launch by 2025




COCKPIT MISSION CONTROL

- ✓ Powerful mission operations tool for monitoring and tasking payloads and constellations
- ✓ Simple external integrations to enable automated and optimized tasking
- ✓ API access or intuitive, web-based UI for users to control their payload with minimal training
- ✓ End-to-end encryption (AES-256)

Thermal Controls	Embedded thermal systems
Data Interfaces	SpaceWire, Ethernet, RS-422/485, PPS, CAN, LVDS Pairs, and others
RF Comms	Up to 1.15 Gbps via X-band S-Band TT&C
Intersatellite Relay Link	200 kbps via Inmarsat AddValue Up to 90% coverage
Onboard Processing	High-speed edge processing and storage via CPU, GPU, and VPU based resources

HUB CAPABILITIES



LOFT ORBITAL

Figure 10: Loft Orbital Satellite Platform

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

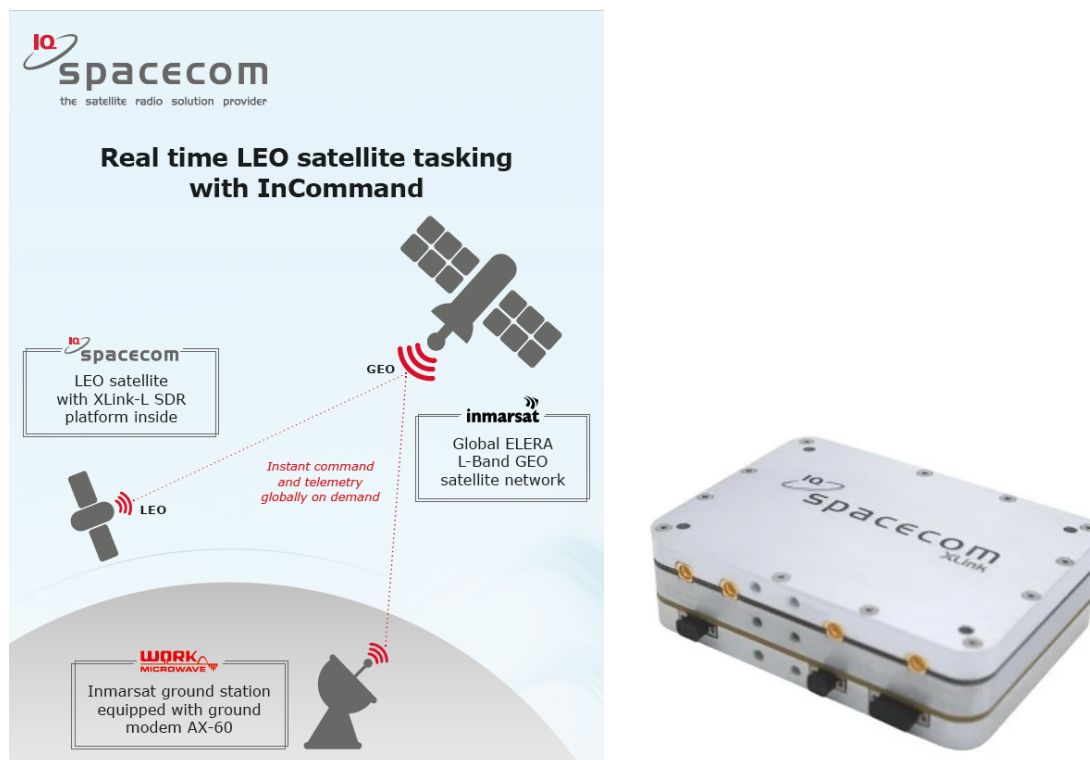


Figure 11: Low cost, lightweight system for instant tasking of small LEO satellites (Inmarsat and IQ spacecom)

6 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 9.

Table 9: 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 10 and Table 11 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.

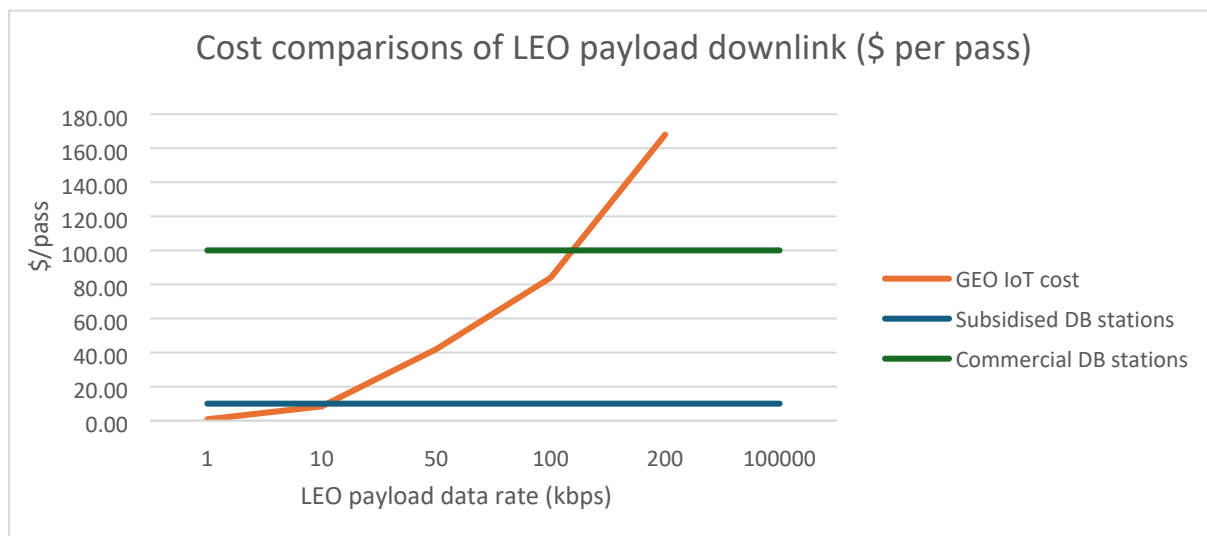


Figure 12: Cost Comparison Analysis of IoT Solutions for LEO Payload Downlink

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 O3B, 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. commercial)

CGMS ensures that data from different national and international satellite systems are compatible, harmonized, and accessible to the global user community through standardised data formats and shared access methods.

A risk exists that the emergence of commercial weather data providers, usage will be restricted to a limited number of agencies. CGMS should ensure that maximum number of users from the meteorological community have access to commercial weather data.

T7. Standards needed for inter-satellite communications.

CGMS should ensure use of standards for inter-satellite link communication. Currently, each relay satellite constellation provides its own modem transponder (e.g. see O2), creating a vendor lock threat. Several transponders are required to connect to several relay constellations.

CCSDS is a credible option to standardise inter-satellite links for CGMS because:

- It matches CGMS interoperability goals
- CCSDS is internationally recognised and used for CGMS best practices on direct broadcast for space to ground communications (CGMS/DOC/18/1008274)
- Can be used for both RF and optical ISLs
- Proven space-to-space heritage (see Mars exploration mission example below)

In terms of tested mission examples, CCSDS's Proximity-1 Space Link Protocol has been implemented on NASA and ESA inter-orbital relay operations, most notably in the Mars exploration context, where orbiters like Mars Odyssey, Mars Reconnaissance Orbiter, and Mars Express used Proximity-1 to exchange data with surface rovers and relay it back to Earth, demonstrating interoperability and relay communications over space links between multiple spacecraft platforms.

7 SWOT CONCLUSION

7.1 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.

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

Use of satellite relay constellations can reduce data latency, improve coverage in regions lacking direct ground contact, and provide resilient network architectures for LEO weather missions, complementing existing ground stations coverage.

Low-latency connectivity in space is rapidly evolving with the emergence of global LEO internet constellations and advances in optical inter-satellite link. Coordination through CGMS to standardised protocols and interfaces definitions is needed to onboard these opportunities.

7.2.1 Telemetry & Telecommand

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.

7.2.2 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 is achieved via a network of ground stations.

7.2.2.1 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.

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

Table 10: 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 11: GEO IoT cost depending on LEO payload data rate. Data volume based on assumption of 14 minutes pass (840s).

APPENDIX B

NEON FACT-SHEET



NEON
NEAR EARTH ORBIT NETWORK

Global Data, Local Weather

Low Earth Orbit (LEO) satellites are the backbone of global long-range weather forecasting models, supplying more than 80% of the numerical weather prediction model data used for 3-7 day forecasts. LEO observations are critical for weather forecasting, environmental observation, and public safety.

SUN	MON	TUE	WED	THU	FRI	SAT
73	75	Windy 20%	Strong Storms 70%	52	Showers 20%	Showers 20%
55	63	63	32	35	46	

NEON

NOAA's Near Earth Orbit Network (NEON) will provide a new approach to developing the next generation global environmental satellite system by launching small to medium-sized satellites with Earth-observing instruments more frequently. NEON will be a resilient constellation of LEO satellites that can be deployed quickly to enhance weather forecasting and disaster management of events like floods and wildfires. NEON's disaggregated approach will evolve the LEO architecture to deploy new observational capabilities through partnerships and commercial or NOAA-developed approaches.

QuickSounder

NEON's first project, QuickSounder, serves as a prototype for NOAA's next generation of LEO environmental satellites. QuickSounder demonstrates that operational observations can be obtained with a small, commercial-based satellite on a compressed schedule.

QUICKSOUNDER

Most NEON satellites will operate in a polar sun-synchronous orbit to ensure global coverage.

BUY AND PARTNER WHERE WE CAN. BUILD WHAT WE MUST.

Together with its partners and commercial industry, NEON will expand the data and modeling capabilities that are vitally important for ongoing weather prediction and environmental monitoring.

Maintaining relationships with domestic and international partners will enable NEON to leverage existing and planned capabilities from other research and operational satellite programs to deliver more key observations to service areas and stakeholders.

Why NEON?

NEON will provide data continuity while addressing new observational requirements more quickly than previous NOAA programs. As a first step, NEON will leverage and advance commercial investment, expertise, and innovation to develop the next generation microwave and infrared sounders that profile atmospheric temperature and moisture and are critical to generating accurate weather forecasts. The global refresh of microwave sounding observations available to the United States will degrade without the NEON program.



Ensures continuous coverage that is critical for a Weather-Ready Nation



Builds partnerships and explores advanced data applications with global user engagement



Provides enhanced remote sensing observations of Earth and its environment for modeling, monitoring, and prediction



Develops cutting-edge technology to more efficiently launch essential new instruments



Supports innovation and continues the data lifeline of preceding LEO satellite programs

NEON Benefits

- Higher resolution data/next generation sensors improve short and long-term weather prediction for National Weather Service forecasts.
- Improved data on phytoplankton and harmful algal blooms aid the Blue Economy and coastal communities.
- Enhanced atmospheric chemistry sensors enable timely and accurate forecasts of air quality hazards.

LEO Observations

Current LEO applications provide invaluable data for a wide variety of scientific and real-life implementations. New instruments, such as the Sounder for Microwave-Based Applications (SMBA) and a next generation infrared sounding instrument, will maintain critical data continuity while beginning to expand our capabilities.

Multipurpose Imagery
Soundings
UV Measurements
LiDAR
Microwave Imagery
Altimetry
Scatterometry
Synthetic Aperture Radar



A collaborative effort between NOAA and NASA, NEON will build and launch small to medium-sized satellites with Earth-observing instruments for weather forecasting and disaster management. NOAA and NASA will work with commercial partners to design, build, and fly the network's spacecraft and instruments.

NOAA's NEON program will supplement and eventually replace NOAA's Joint Polar Satellite System (JPSS), laying the groundwork for the next generation of LEO satellites before the final JPSS launch in 2032.

nesdis.noaa.gov/neon