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OPTICAL GROUND STATION NETWORK OPTIMIZATION AND PERFORMANCES FOR HIGH DATA RATE GEOSATELLITE-TO-GROUND TELEMETRY

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I. INTRODUCTION

Optical data links with high data throughput aim at answering the increasing capacity demand for downloading data issued from observation, meteorology and scientific satellite payloads without the need for Radio Frequency (RF) coordination. Expectation of continuous near real-time services leads to very high availability requirements for the Optical Ground receiving Station (OGS) network. Evaluation of the N Optical Ground Station Network (N-OGSN) availability is commonly based on Clouds Masks (CMs) derived from multi-band imagers data on board satellites. Optical communications require clear sky propagation conditions and the N-OGSN is available if at least one of the N optical ground stations is clear sky. Optimizing the network corresponds to maximizing its availability during a full year. This can be performed by both minimizing the probability of clouds over the OGSs and minimizing the weather correlation between OGSs sites. [1]. optimize the OGS localization in Europe for LEO downlink mission among a discrete list of preferred sites preselected according to their low ranking of probability of clouds. [2]. address the scenario of deep space to ground optical communication and optimizes the OGSN by testing all the possible combinations of OGS localization in restricted zones over different continents. CMs with the higher temporal and spatial resolutions shall be selected to reduce the uncertainty on the availability results. This paper presents a methodology aiming at optimizing the availability of an N-OGSN composed by a main OGS (OGS1) and (N-1) redundant OGSs for geostationary satellite to Earth station high data rate telemetry. The optimization of the OGS localizations composing the network is assessed on the basis of weather correlation between sites. The idea is to maximize the conditional opposite weather conditions between OGS1 and the redundant (N-1) OGS localizations. The accuracy of the availability computation is assessed taking into account two sources of uncertainty. First, the uncertainty dues to the potential clouds motion during the 15 minutes separating two successive snapshot Cloud Masks (CMs). Second, the statistical uncertainty related to the number of CMs in the experimental databank. Worst case availability results and time distribution of network unavailability of the optimized optical ground station network are presented. The design of the optical ground station network and its performances evaluation are based on SAF-NWC Cloud Masks provided by Meteo France to CNES and computed from Meteosat Second Generation (MSG) data. In section II, we present the case of study, the experimental data used for the study, and the hypotheses. In section III, the optimization of the locations of the (N-1) redundant OGSs is described and performed. In section IV, the performances of the optimized N-OGSN are compared with the benchmark network proposed in [1]. Section V concludes the papers and suggests some perspectives for improvements.

II. CASE OF STUDY, EXPERIMENTAL DATBANKS AND HYPOTHESIS

A. Case of study

The geostationary (GEO) satellite is at orbit position 16°Est. The geographical Zone of Interest (ZoI) selected to implement the OGSs is centered on Europe from 10°W to 30°E in longitude and 30°N to 51°N in latitude. The data are issued either directly from payloads on-board the GEO satellite or from payloads on-board LEO satellites. In that second scenario, the GEO satellite is a data relay satellite which is assumed to be a real-time high-availability link (bent pipe). For both scenarios, the required availability for the GEO-to-ground optical link is arbitrarily fixed at 99.5% over the year. CMs are directly applicable to our case of study because these are derived from geostationary MSG satellite data.

B. Experimental databanks

Fig.1 illustrates the Clouds Masks (CMs) that were provided by the French National Meteorological Agency (Meteo France) on the basis of the SAF NWC clouds classification dealing with data from MSG1 and MSG2. The primary mission of MSG satellites is the continuous observation of the earth's full disk. This is achieved with the Spinning Enhanced Visible and Infrared Imager (SEVIRI) imaging radiometer. SEVIRI is a 12-channel imager observing the earth–atmosphere system with a 15-min repeat cycle. From the 12-channel images, CMs are snapshot products derived every 15-min. The characteristics of the CMs are the following:

- Data length: 1 year (2008)
- Spatial resolution : 4.4km x 4.4km
- Time resolution: 15 minutes
- Pixel types: clouds classification from SAF NWC codes ([3].):
  - Clear Sky (CS): code {1, 2, 3 and 4} in yellow in **Fig.1**;
  - Cirrus = code {15,16,17} in blue;
  - Cloudy: other codes in grey.
- Zone of interest: [10°W;30°E] [30°N;51°N]
- 2008 MSG1: 4°W till March, 9.25°E then.
- 2008 MSG2: 0.5°W.
- Product type: Snapshot mask

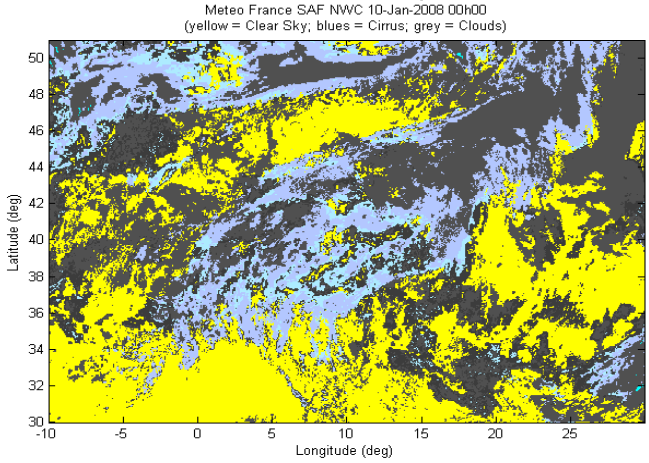

Fig.1 Meteo France Cloud Mask 01-01-2008 (00h00)

C. Definitions and hypotheses

An OGS will be declared available only if its corresponding pixel in the CM is of "Clear Sky" type (code 1, 2, 3, and 4 of the SAF NWC clouds classification). To cope with possible cases of missing data, the dataset is pre-processed with the following rules. If the duration of missing data is less than 1 hour and the pixel types of the two CMs surrounding the missing period are the same, we consider the same pixel type for the missing data. Otherwise, we consider in a worst case approach that there were clouds during the entire missing period. The Quality Indicator (QI) of the experimental databank is computed over time period - month or year – according to (1):

$$QI = \frac{Number_{missing\ data}}{Number_{data}} \quad (1)$$

The quality indicator is the upper limit ($\leq 100\%$) of the availability that is reachable regarding our unperfected experimental databank and worst case approach without taking into consideration uncertainty. It corresponds to the availability of an infinite OGSN and it possibly decreases the availability results of any finite N-OGSN, particularly when we aim at very high availability requirements.
CM is based on 12-channel snapshot images where the exposure time for every pixel is around 0.1 milliseconds so it is not the result of integration over 15 minutes. We assume no formation or disappearance of clouds during the 15 minutes but we need to address the case were a neighboring cloudy pixel pushed by the atmosphere wind comes to intercept an OGS location within the time [T_0; T_{0+15}]. At the time of the study we did not have access to the statistic of cloud motion speeds so we estimated it with the atmosphere turbulences wind speed and the wind from the advection motion vector at 720 hPa. The two estimates evaluate the cloud motion speed lower than $\overrightarrow{v_{cloud}} = 27m.s^{-1}$ in 99.5% of the cases.

III. OPTICAL GROUND STATION NETWORK OPTIMIZATION

A. Methodology

A solution to reach such high availability requirement during the year as 99.5% while keeping a small number of OGS in the ground network is the following iterative process:

- First: locate the main OGS where there is the lowest probability of clouds.
- Then, for each of the (N-1) redundant OGS, $OGS_i \,/\, i \in [2{:}N]$: select its location on the ground maximizing the probability of clear sky when the (i-1)-OGSN is not available, i.e. when there is no OGS available in the (i-1)-OGSN. We do not consider the opposite case where the (i-1)-OGSN is available and redundant sites are cloudy – cases that are incorporated in the notion of global weather decorrelation – which are not interesting for our aim and could biases the results. **Fig.1** and **Fig.2** present respectively the probability in percentage of conditional opposite weather conditions with OGS1 (iteration i = 2) and with the optimized 5-OGSN (iteration i = 6). The access to the entire CMs databanks is very time consuming so it was preferred to not test the availability of the (i)-OGSN at

each step. The maximum number of OGS in the OGSN is overestimated and arbitrarily fixed during the OGSN optimization (e.g. N=10).

- The result is the optimized N-OGSN. We can restrict the number of OGS in the network at posteriori if smaller N-OGSN satisfies the mission requirements.

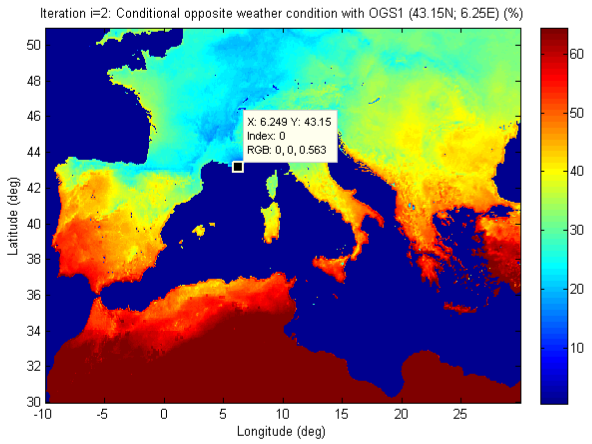

Fig.2. Probability (% over 2008) of conditional opposite weather condition with OGS1 in the ZoI

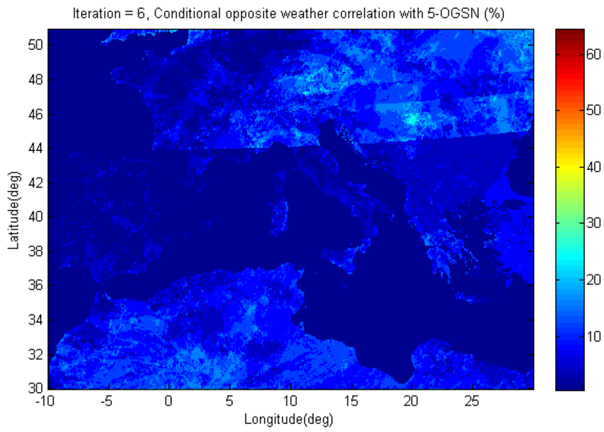

Fig.3. Probability (% over 2008) conditional opposite weather condition for the 5-OGSN in the ZoI

In this paper, the main OGS has been located at [43.15°N; 6.25W] so that the performances of the optimized 6-OGSN can be compared with the results of [1].

B. Results

At each step we have to access to the entire CMs databanks which is time consuming, so the optimization process for an N-OGSN takes $T_{N-OGSN_{optimization}} \approx N * 3\,[hours]$ on a machine with Dual Core 2,1GHz and 4GHz RAM. **Tab.1** shows the optimized 6-OGSN re-classified by order of geographic proximity to the main OGS [43.15°N; 6.25E].

Tab.1. Optimized 6-OGSN in the ZoI (over 2008)

Optical Ground Station	OGS1	OGS2	OGS3	OGS4	OGS5	OGS6
Latitude (°)	43.15N	44.30N	31.15N	31.63N	30.71N	30.02N
Longitude (°)	6.25E	15.31E	8.76E	22.96E	9.8W	29.27E
Orthodromic distance from OGS1 (km)	0	741	1350	1949	1981	2510

IV. OPTICAL GROUND STATION NETWORK PERFORMANCES

The input parameters for the computation of the final N-OGSN availability, Ava_{N-OGSN}, are:

- Definition of availability at OGS level: “An OGS is available only if its correspondent pixel in the CM is of type “clear sky” (code 1, 2, 3, and 4 of the SAF NWC clouds classification)”;
- Localization of the OGSs (latitude ;longitude) of the network;
- Handover hypothesis: For the present study, we assumed instantaneous handover between OGSs.

A. Methodology and post-processing

First, we evaluate an estimator of N-OGSN availability computation Est_{N-OGSN} by checking the availabilities of the OGSs at every time slot and for the entire databank length of CM. The N-OGSN is available is at least one of the OGSs is available, otherwise the N-OGSN is declared unavailable. In the case where the main OGS is cloudy, we store the duration of the main OGS unavailability and the duration of the handover(s) (durations can be different). The OGSs are selected for the handover according to their geographic proximity to the main OGS.

The post-processing aims at estimating an error box around the estimator Est_{N-OGSN} to compute a final availability result Ava_{N-OGSN} that takes into consideration uncertainties. There are two sources of uncertainty:

- Firstly, the uncertainty related to the probability P_{w_i} of misestimating the state of OGS_i because of possible cloud motion during the time interval [T_0; T_{0+15}]. P_{w_i} depends on the weather correlation P_{corr_i} in the square of size $d = 2.\frac{\|v_{cloud}\|.(15*60)}{1000} = 48.6\ [km]$ centered on OGS$_i$. Considering that the cloud motion speed is isotropic, that the duration of misestimating is the complete time resolution 15 , and that the probability of error on the OGS$_i$ state estimator is independent from the value of the estimator, we have the following relation (2) between P_{w_i} and P_{corr_i}:

$$P_{w_i} = 1 - P_{corr_i} \quad (2)$$

Tab.2. Weather correlation in the 48.6km^2 square around the 6 OGSs of the network (over 2008)

Number	OGS1	OGS2	OGS3	OGS4	OGS5	OGS6	Average
P_{w_i} (%)	87.92	86.44	91.69	90.8	87.12	91.01	89.16

We assume for the uncertainty box calculation that the OGSs weather conditions are the same – i.e. $P_{w_i} = P_w$ *and* $P(a_i) = P(a), \forall\ i\epsilon\mathbb{N}^*$ – and are independent. Under these hypotheses, we can define a factor of degradation F due to possible cloud motion between [T$_0$; T$_{0+15}$] that is illustrated on **Fig.3**.

$$F = [1 - [P(a)]^N] - \left[1 - \left[(1 - P(a))P_w + P(a)(1 - P_w)\right]^N\right]$$

$$F = \left[(1 - P(a))P_w + P(a)(1 - P_w)\right]^N - [P(a)]^N$$

Where, $P(a)$ is the average probability over the N-OGSN of the event a =" OGS state NOT available" and P_w is the average of the P_{w_i} in the N-OGSN (see **Tab.2.)**

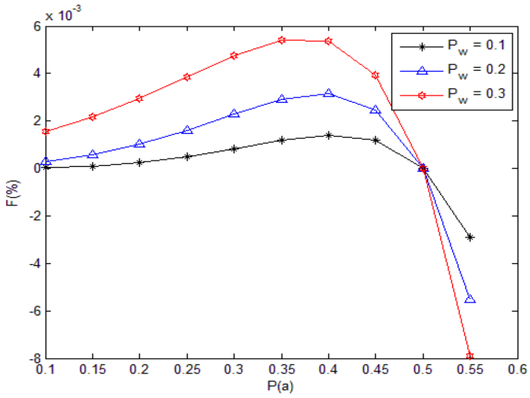

Fig. 3. Cloud motion uncertainty factor F

- Secondly, the uncertainty inherent to statistic estimation dependent on the size $N = 365 * 24 * 4 = 35040$ over a year ($N = 30 * 24 * 4 = 2880$ over a month) of the experimental databank has to be addressed. Assuming that the different realizations of the databank of CMs are independent and stationary over the time, the N-OGSN availability estimation is modelled by a Bernouilli process of parameters, $p = Est_{N-OGSN}$, $q = 1 - p$, and standard deviation $\sigma = \sqrt{pq}$. From the large number mathematical law, the interval of confidence at x.σ around Est_{N-OGSN} is +/- $\frac{x.\sigma}{\sqrt{N}}$, where x is set to 3 to have the confidence interval at 99.7%. The difference between Est_{N-OGSN} and the lower bound of the interval of confidence at 3σ is noted G.

Eventually, the availability of the N-OGSN is calculated according to (3):

$$Ava_{N-OGSN} = Est_{N-OGSN} - F - G \quad (3)$$

B. *Results*

The performances of the optimized 6-OGSN presented in **Tab.1** is compared with the network taken as benchmark for the study showed in **Tab.2** below.

Tab.2. Benchmark Optical Ground Station Network suggested in **[1].**

Optical Ground Station	OGS1	OGS2	OGS3	OGS4	OGS5	OGS6
Latitude (°)	43.15N	42.35N	41.75N	46.75N	39.45N	36.65N
Longitude (°)	6.25E	1.05E	12.35E	1.95W	7.35W	22.95E
Orthodromic distance from OGS1 (km)	0	434	535	760	1257	1596

Fig. 4 illustrates the estimator (Est_{N-OGSN}) and the final value (Ava_{N-OGSN}) of the availability for both 6-OGS networks. It can be seen that the estimator of the optimized 6-OGSN availability reaches the upper limit QI (availability of an infinite OGSN). So, considering our unperfected experimental databank and worst case approach it would be useless to add new redundant OGS. The final availability Ava_{N-OGSN} of the optimized 6-OGS network is superior to the required availability of 99.5%.

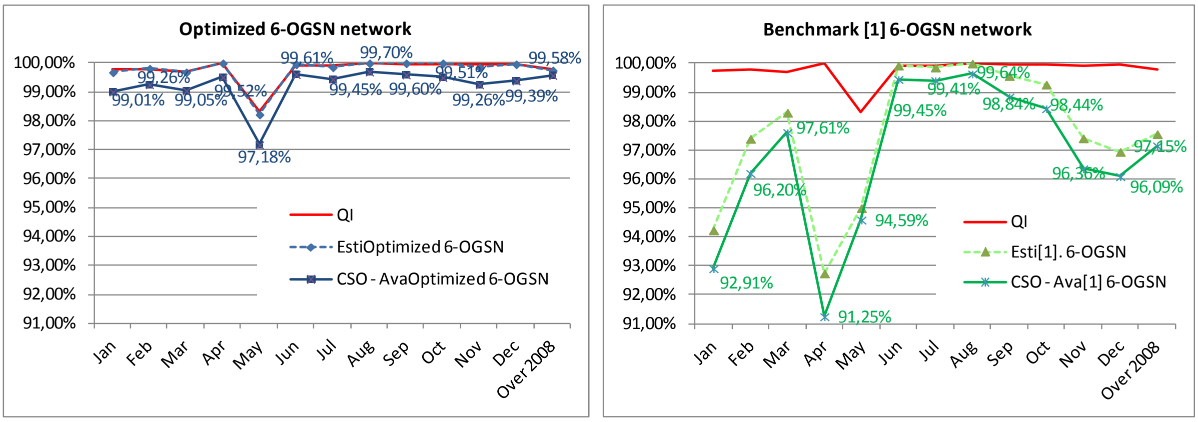

Fig. 4. Availability result of the optimized 6-OGSN vs benchmark 6-OGSN

Fig. 5. shows the unavailability time duration of the optimized 6-OGSN vs benchmark 6-OGSN.

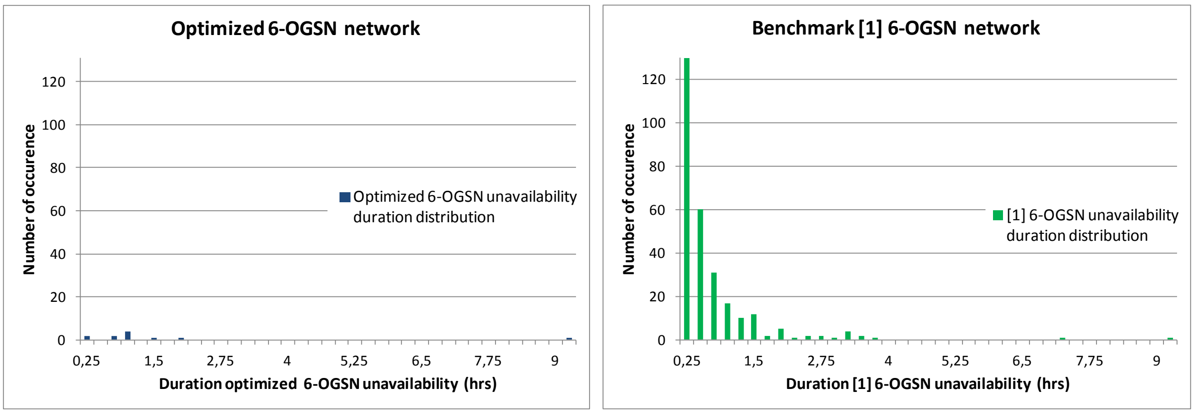

Fig. 5. Unavailability time duration distribution of the optimized 6-OGSN vs benchmark 6-OGSN

Tab.3 presents the potential impact of no-instantaneous handover on the availability results assuming either a dedicated optical fiber network or a shared optical fiber network between the OGS. Restoration time takes into consideration only the ground optical fiber network and do not address issues related to the end-user side.

Tab.3. Potential impact of handover on availability of the N-OGSN

CSO		Optimized 6-OGSN	Benchmark 6-OGSN [1]
Number of handover		1098	1536
Unavailability duration (% of the year)	Dedicated fiber network (restoration time ~50ms)	0,0002%	0,0002%
	Shared fiber network (restoration time ~10s)	0,04%	0,05%

V. CONCLUSION AND PERSPECTIVES

A new methodology for the optimization of OGS location has been presented and described. The results show that the availability of the optimized OGS network outperformed the network extracted from [1] which was taken as benchmark. Such methodology has great impact for the optimization of N-OGSN and offers the opportunity of designing small OGS network compliant with very stringent availability requirement. The optimized 6-OGSN reaches 99.58% availability over the year with 1536 handover between the OGS in the network. Considering only the optical fiber network, handovers within a shared optical fiber network between OGS can decrease the availability to 99.53% what is still over the 99.5% availability requirement. In the future, the main site (OGS1) could benefit from multiple optical terminals within a restricted zone to increase its availability and so decrease the number of handover. Regarding the optimization method, the ZoI will be increased and criteria such as proximity to the optical fiber network will be taken into consideration. Also, the experimental databank length and quality will be increased.

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