OPTIMAL LOCATION OF OPTICAL GROUND STATIONS TO SERVE LEO SPACECRAFT

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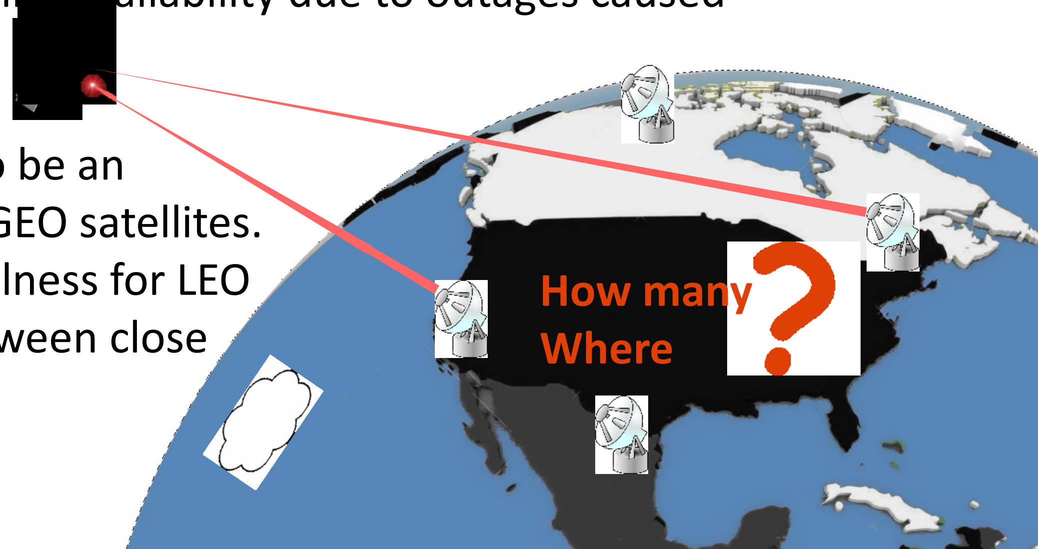
Introduction

There are three main reasons that are driving the deployment of optical technology for space communications.

- Higher data volume request by users:
  - Constellations of small EO satellites demand more data (i.e., Planet constellation ~ 6Tb /day)
  - High-resolution wide-swath sensors and SAR require datarates in the order of Gbps.
- Lower Size Weight and Power (SWaP)
- Optical Spectrum is unlicensed

The main drawback is the reduced li[redacted]ailability due to outages caused by cloud coverage over the receiving ground stations.

- Site diversity has been proven to be an effective mitigation technique for GEO satellites.
- However, it is not clear it's usefulness for LEO missions due to the correlation between close ground stations



Outline

- **Introduction**
- **Research Objective**
- **Our approach**
  - Cloud model description
  - Scenario description
  - Network availability computation
- **Results**
  - Constrained scenario
  - Unconstrained scenario
- **Conclusions**

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Research Objective

- The problem of optimal location for optical ground stations to serve satellites in GEO has been previously studied, both using…
  a) Historical time series of cloud occurrences [Wojcik'05], [Fuchs'15], [Poulenard'15]
  b) Analytical approaches [Perlot'12], [delPortillo'16]
- Not so much work has been conducted to determine the optimal locations for optical ground stations in scenarios in which satellites are in LEO.

> The objective of this paper is to determine the optimal locations for a network of OGSs that serve space-missions in LEO. In particular we want to identify the sites that are Pareto-optimal with regard to the main network performance drivers.

Performance drivers:

- **Network availability:** as percentage of the orbit-time that a satellite can access an OGS to download the data stored.
- **Cost**: defined as the construction and operation costs incurred to maintain operative the ground assets that form the network.
- **Latency:** interval between two consecutive successful contacts between the satellite and an OGS.

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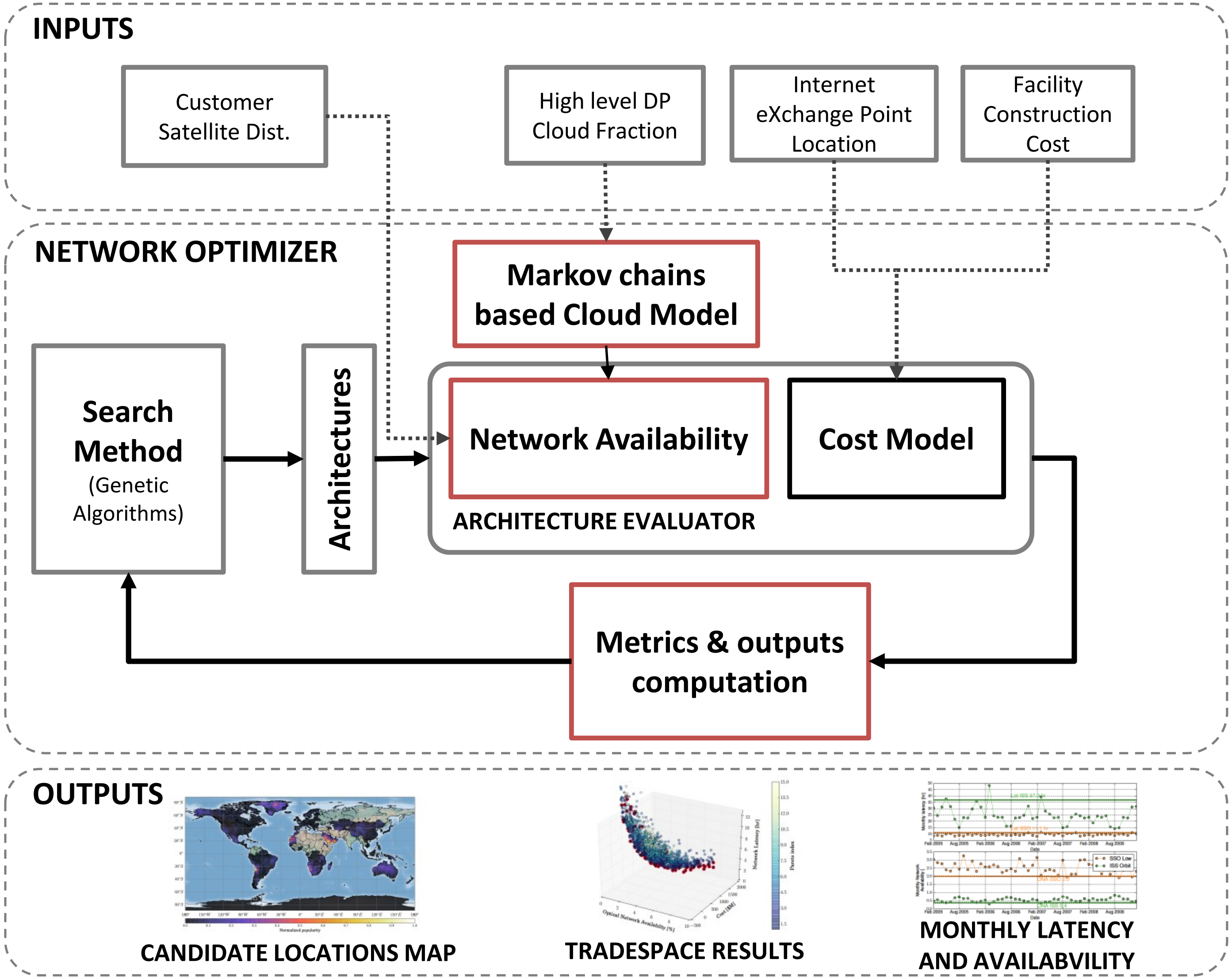
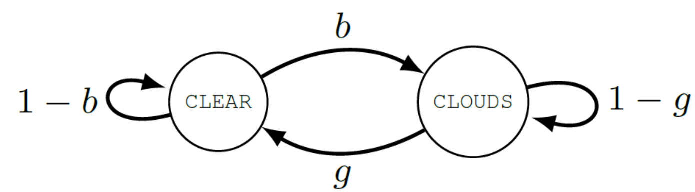
Overall picture



Cloud Model

Single ground station

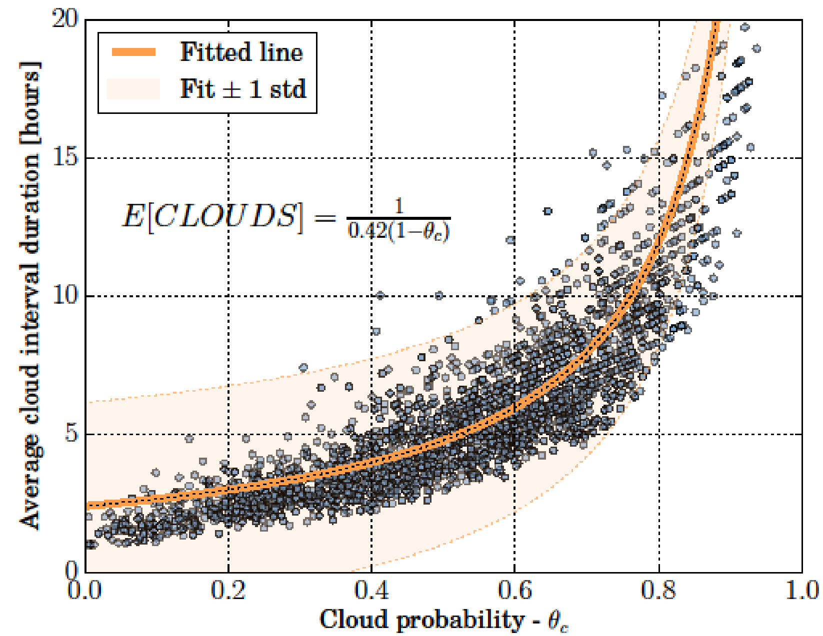
- Two state Markov chain (Gilbert-Elliot model) as proposed in [1].
- Two parameters (g and b) need to be estimated using:
  - Expected time in CLEAR and CLOUDS states (π_G, π_B)
  - Sojourn time: Expected duration of a cloud interval. E[CLOUDS]



$$\boldsymbol{T} = \begin{bmatrix} 1-b & b \\ g & 1-g \end{bmatrix}$$

Estimation of the sojourn times

- Experimentally determine the average duration of the cloud intervals, E[CLOUDS], using 2-hour frequency satellite imagery data captured by EUMETSAT during the years 2005, 2006, and 2011.



[1] L. Clare and G. Miles, “Deep space optical link ARQ performance analysis,” in 2016 IEEE Aerospace Conference, March 2016, pp. 1–11.

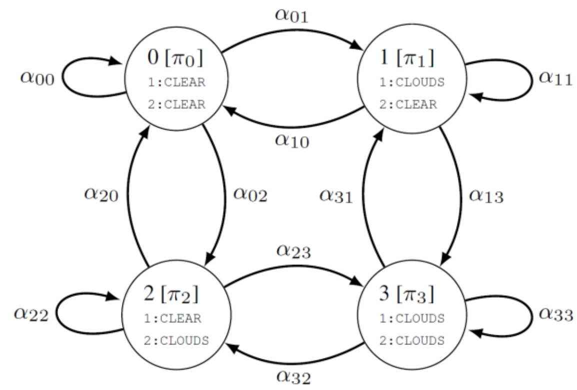
Cloud Model

Two correlated ground stations

- Four state Markov chain.
- Assume that only one ground station can change its state between consecutive samples
- Twelve parameters need to be estimated (α_{ij})
  - Marginal and joint cloud probabilities on each site.
  - Marginal and joint sojourn times.
- Step 1: Determine the stationary probabilities
  - Exact solution using correlation factor [2] and marginal site probabilities

$$
\begin{aligned}
\pi_0 &= (1-\theta_c^{(1)})(1-\theta_c^{(2)})(\rho\theta_c^{(1)}\theta_c^{(2)}+1) \\
\pi_1 &= \theta_c^{(1)}\left(1-\theta_c^{(2)}\right)\left(1-\rho\theta_c^{(2)}(1-\theta_c^{(1)})\right) \\
\pi_2 &= \theta_c^{(2)}\left(1-\theta_c^{(1)}\right)\left(1-\rho\theta_c^{(1)}(1-\theta_c^{2})\right) \\
\pi_3 &= \theta_c^{(1)}\theta_c^{(2)}\left(\rho\theta_c^{(1)}\theta_c^{(2)}-\rho\theta_c^{(1)}-\rho\theta_c^{(2)}+\rho+1\right)
\end{aligned}
$$

- Step 2: Determine the transition probabilities
  - Numerical solution of 12x12 system using sojourn times and stationary probabilities.



$$
\boldsymbol{P} = \begin{bmatrix} \alpha_{00} & \alpha_{01} & \alpha_{02} & 0 \\ \alpha_{10} & \alpha_{11} & 0 & \alpha_{13} \\ \alpha_{20} & 0 & \alpha_{22} & \alpha_{23} \\ 0 & \alpha_{31} & \alpha_{32} & \alpha_{33} \end{bmatrix} \qquad \Pi = \begin{bmatrix} \pi_0 \\ \pi_1 \\ \pi_2 \\ \pi_3 \end{bmatrix}
$$

$$
\boldsymbol{P}\,\underline{\mathbf{1}} = \underline{\mathbf{1}} \;\rightarrow\; \sum_{j=0}^{3} \alpha_{ij} = 1, \quad \forall i = 0,1,2,3
$$

$$
\boldsymbol{P}\,\boldsymbol{\Pi} = \boldsymbol{\Pi} \;\rightarrow\; \sum_{j=0}^{3} \pi_j \alpha_{ij} = \pi_i, \quad \forall i = 0,1,2,3
$$

$$
E[\text{CLOUDS}^{(1)}] = \frac{T}{g_1} \qquad E[\text{CLOUDS}^{(2)}] = \frac{T}{g_2}
$$

$$
E[\text{STATE}_3] = T\left(1-\frac{1}{\alpha_{33}}\right)
$$

$$
E[\text{STATE}_0] = T\left(1-\frac{1}{\alpha_{00}}\right)
$$

[2] P. Garcia, A. Benarroch, and J. M. Riera, “Spatial distribution of cloud cover,” International Journal of Satellite Communications and Networking, vol. 26, no. 2, pp. 141–155, 2008.

Scenario description: Customer base description

LEO satellites characteristic orbits

- The customer user base is assumed to be similar to the current user base of LEO missions with scientific, Earth observation and weather monitoring purposes.
- A total of 331 satellites were identified using STK satellite database
- These satellites were manually classified into 7 groups that represent 80% of the current satellites.
- Of those, 80 % of the satellites belong to SSO orbits, 13 % to the ISS orbit, 7% to others.

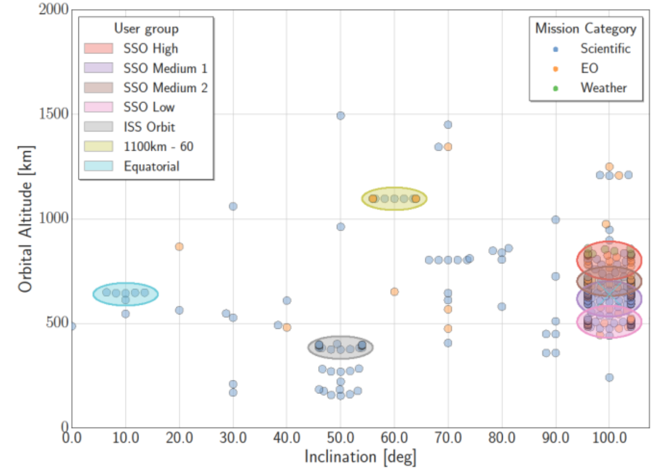


Table 2. Orbital characteristics of LEO satellites with scientific, weather or Earth observation missions

ID	Name	Inc [deg]	Alt [km]	Inc min [deg]	Inc max [deg]	Alt. min [km]	Alt. max [km]	Comments	# Sat. #	Weight [%]
1	SSO High	98.5	802	98.41	98.72	758	859	All weather satellites, and several EO satellites	33	13.10
2	SSO Medium 1	97.87	617	97.37	98.37	553	647	Similar number of scientific and EO satellites	62	24.60
3	SSO Medium 2	97.9	702	97.67	98.3	665	743	Mostly scientific satellites	39	15.48
4	SSO Low	97.5	508	97.2	98.2	475	560	Similar number of Scientific and EO satellites	64	25.40
5	ISS Orbit	51.64	385	51.63	51.64	375	402	A large number of cubesats deployed from the ISS	33	13.10
6	1100 km -60	63.4	1097	63.37	63.41	1097	1097	Composed by the Yaogan constellation	15	5.95
7	Equatorial	6.0	640	5.99	6.02	613	649	Scientific satellites (LEMUR, Nustar, ASTROSAT)	6	2.38

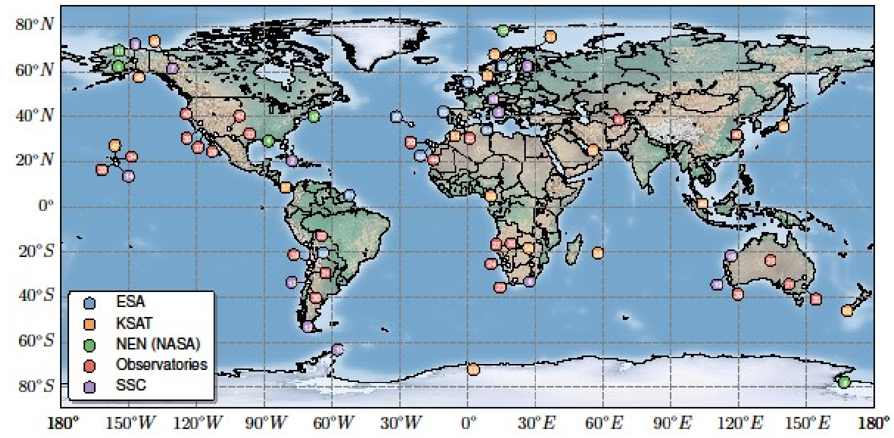
Table 2. Characteristics of the user-base considered for the analyses

Scenario description: Location of OGSs

Fixed candidate set scenario

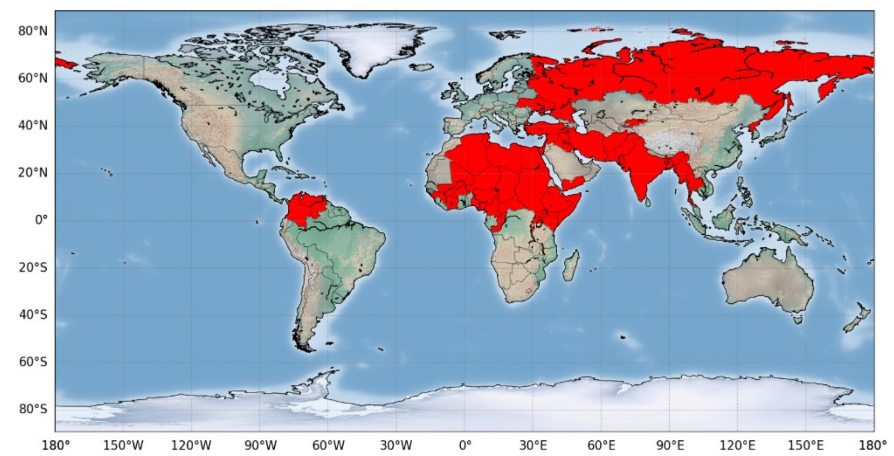
Candidate locations for the ground stations include:

- NASA facilities (NEN)
- ESA facilities
- KSAT facilities
- SSC facilities
- Astronomical observatories



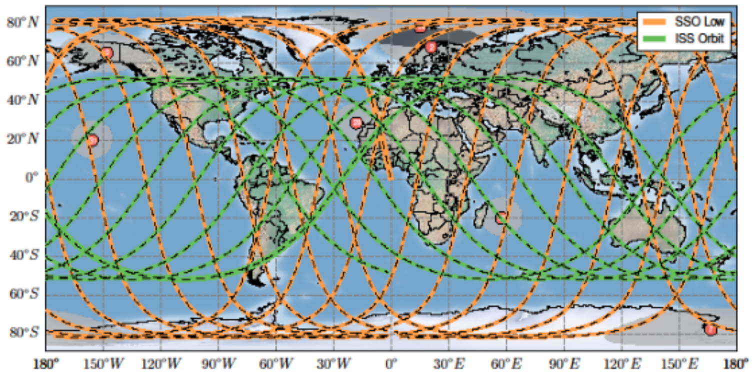
Unconstrained scenario

Any point of land with the exception of the countries that rank on the bottom 20% of the "*Political Stability and Absence of Violence/Terrorism*" index from the "*Worldwide Governance Indicators*" dataset of the WorldBank .

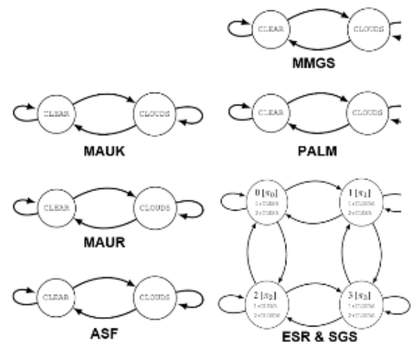


Network availability evaluation

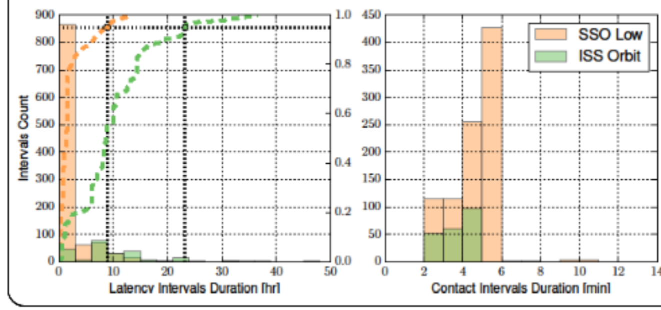
1 Create line of sight mask for each OGSs in the network and propagate customers orbits

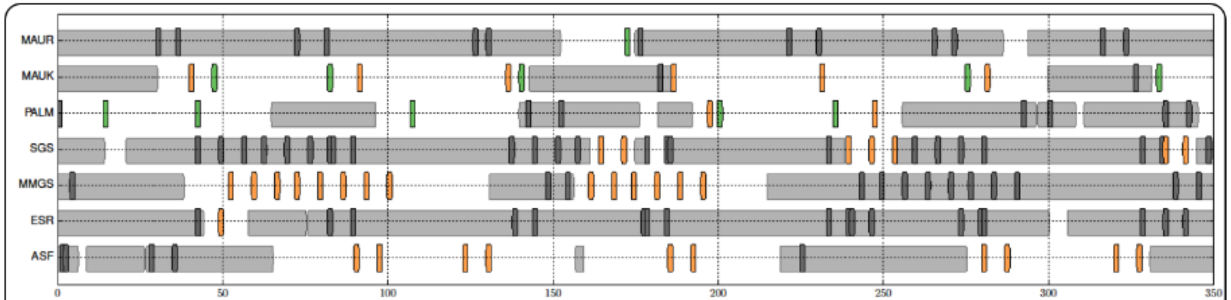


2 Build stochastic weather generator model for the network. Independent OGS are a Gilber-Elliot Markov chain, whereas correlated OGS are represented by a 4 state Markov chain.

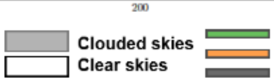


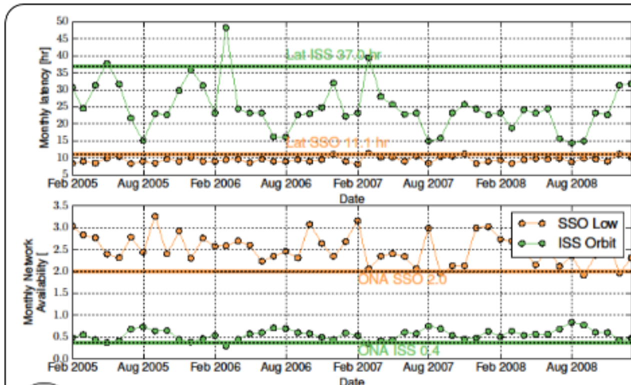
4 Analyze for each month, the latency and contact interval duration distributions. Compute the monthly network availability (NA_m) and the monthly latency (lat_m)





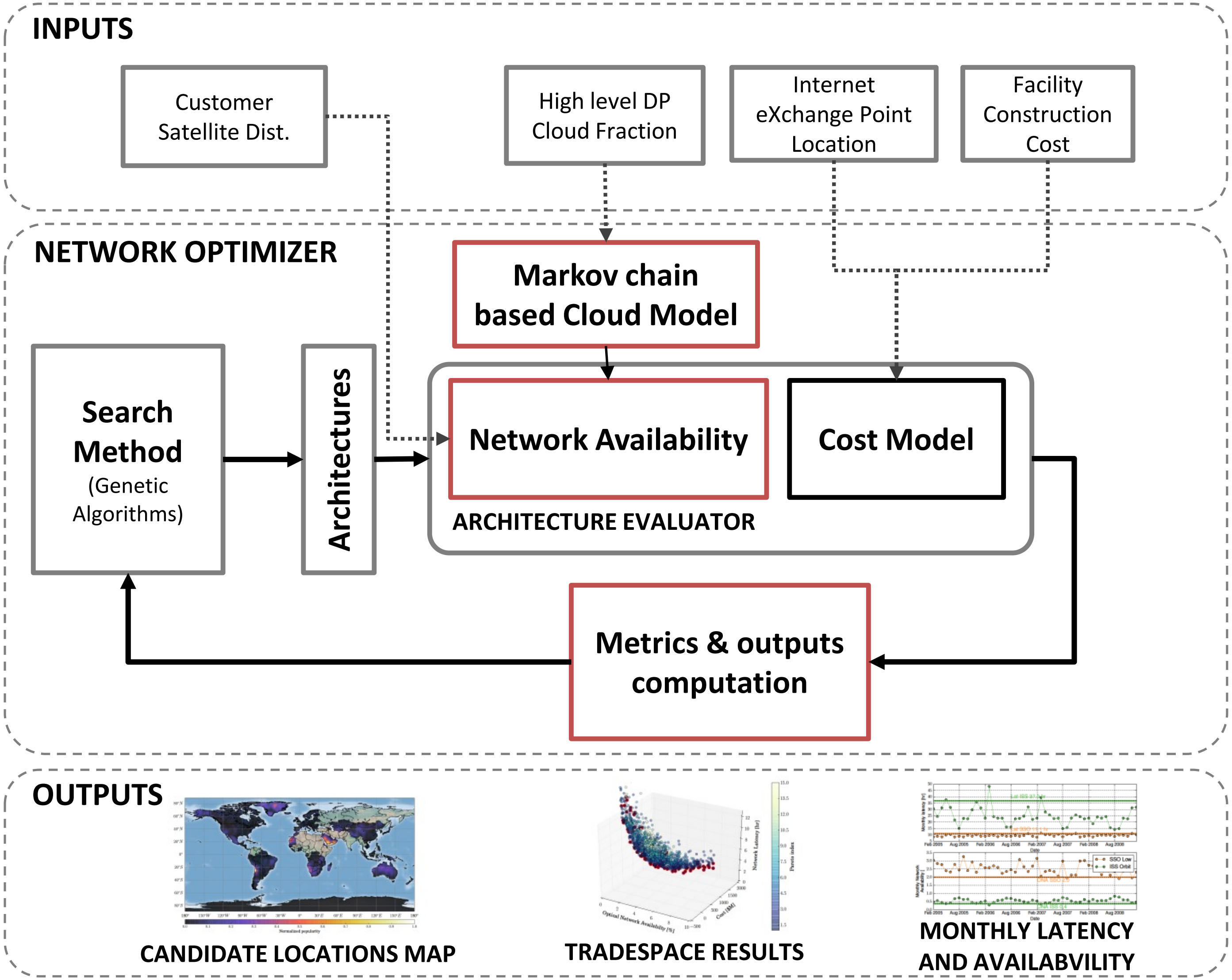
3 Compute cloud and visibility intervals and determine contact times, and latency times





5 Aggregate monthly values to obtain the optical network availability (ONA) and overall latency (lat) metrics

Overall picture



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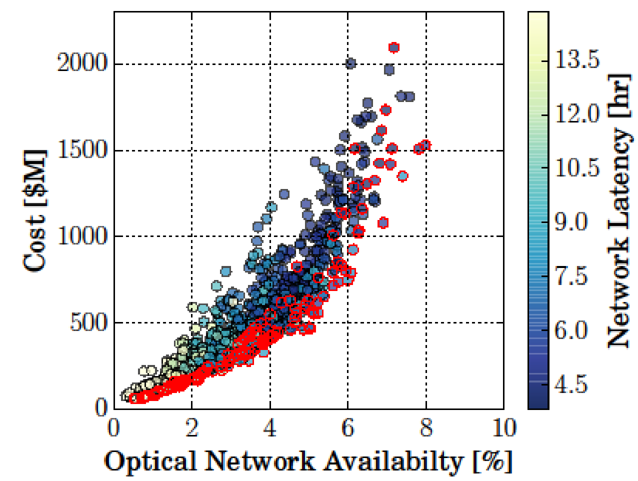
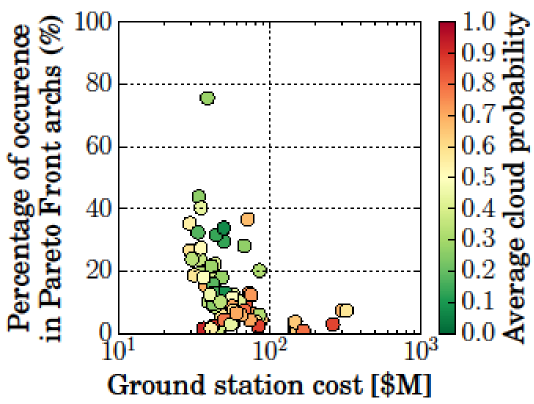
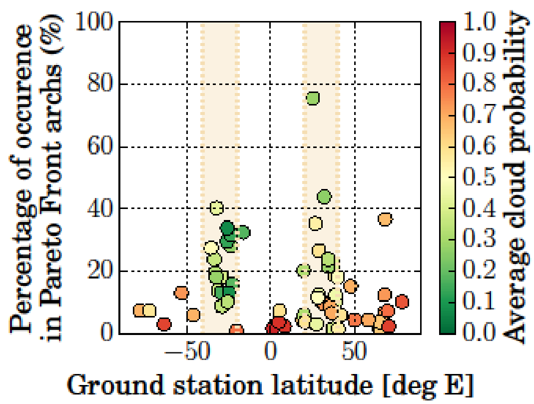
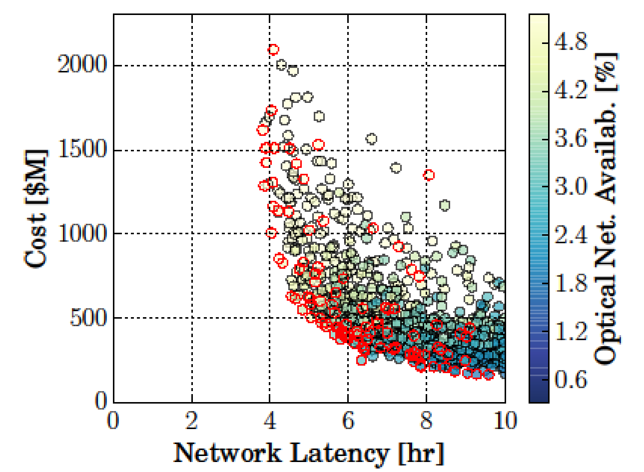
Results – LEO satellites: Candidate set of locations

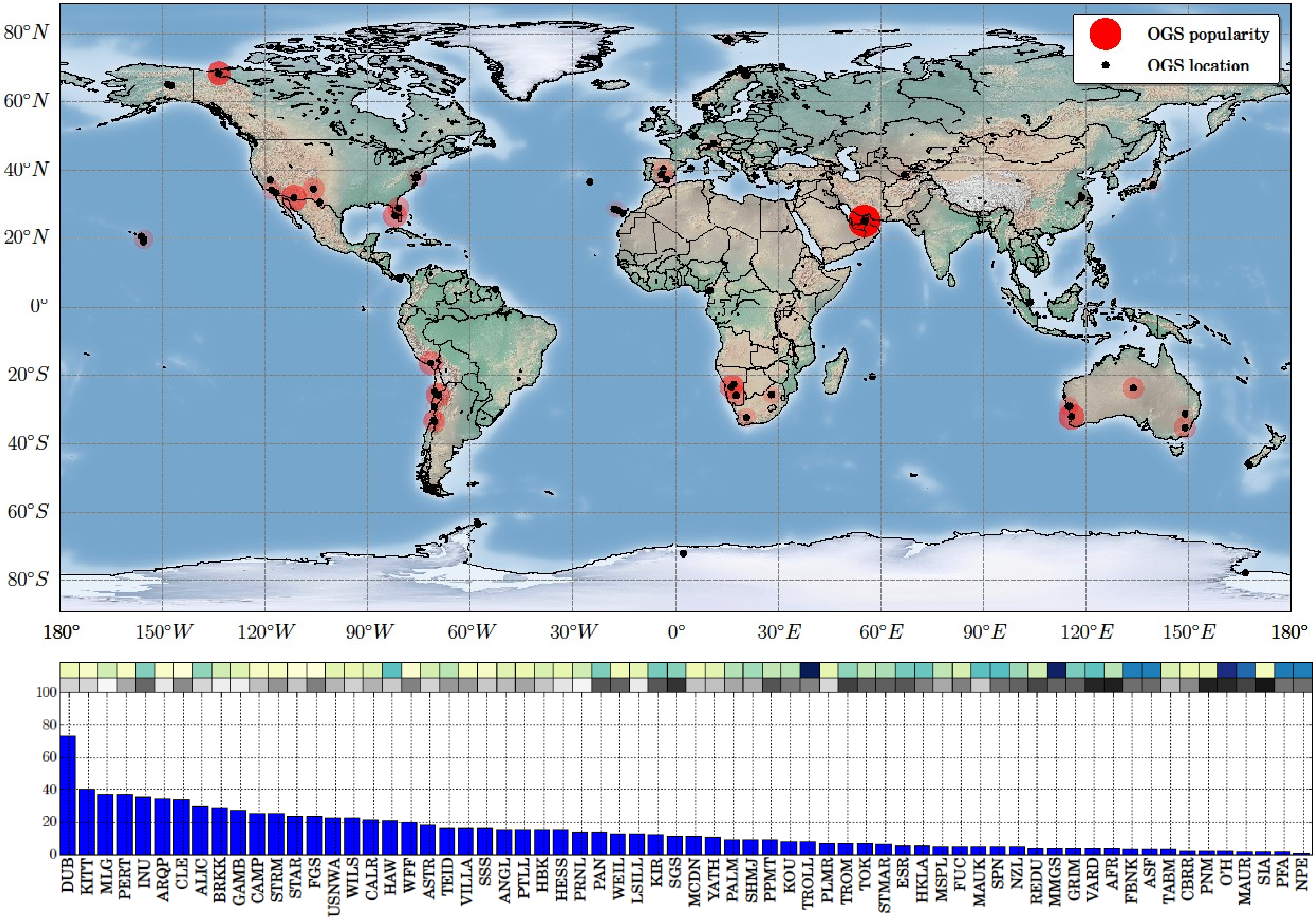
- More than 200,000 architectures with 3 to 20 OGSs were analyzed.
- The minimum latency achieved was 4 hours, while the maximum ONA obtained was ~ 8 %. This availability is approximately half of what the equivalent RF network would achieve.
- The mean cloud probability had a higher impact than cost on the popularity of an OGS.
- The most popular locations are located in the 20-40 latitude band (both North and South hemisphere) and correspond to astronomical observatories.







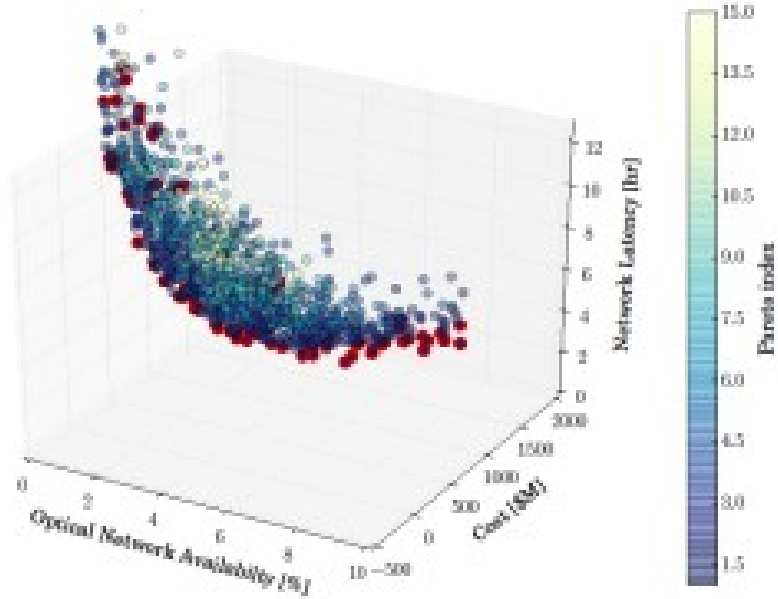


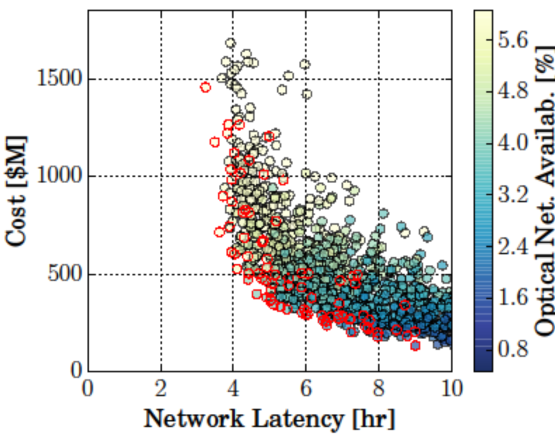


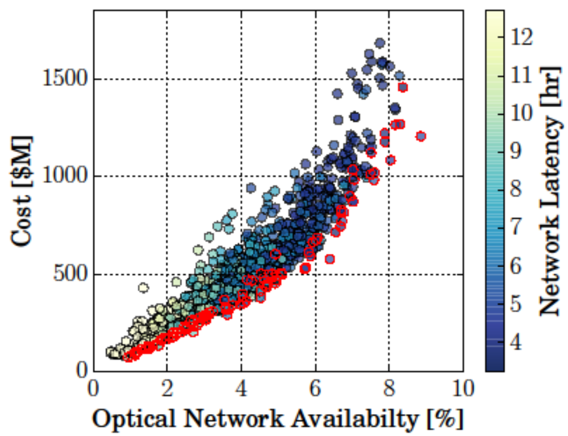
OGS popularity
OGS location
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
80°S
180°
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E
180°
100
80
60
40
20
0
DUB
KITT
MLG
PERT
INU
ARQP
CLE
ALIC
BRKK
GAMB
CAMP
STRM
STAR
FGS
USNWA
WILS
CALR
HAW
WFF
ASTR
TEID
VILLA
SSS
ANGL
PTLL
HBK
HESS
PRNL
PAN
WEIL
LSILL
KIR
SGS
MCDN
YATH
PALM
SHMJ
PPMT
KOU
TROLL
PLMR
TROM
TOK
STMAR
ESR
HKLA
MSPL
FUC
MAUK
SPN
NZL
REDU
MMGS
GRIM
VARD
AFR
FBNK
ASF
TABM
CBRR
PNM
O'H
MAUR
SIA
PFA
NPE

Results – LEO satellites: Unconstrained optimization

- A variable length chromosome GA was used to determine the optimal locations (over 2M architectures were evaluated).
- The minimum latency achieved was 3.25 hours (vs 4 hours in the constrained scenario), while the maximum ONA obtained was 8.85 % (vs. 8 %).
- The total cost of the network decreases (mainly due to the presence of OGSs in what the cost model considers “cheap” countries, not considered in the previous analysis. (Morocco, Saudi Arabia)







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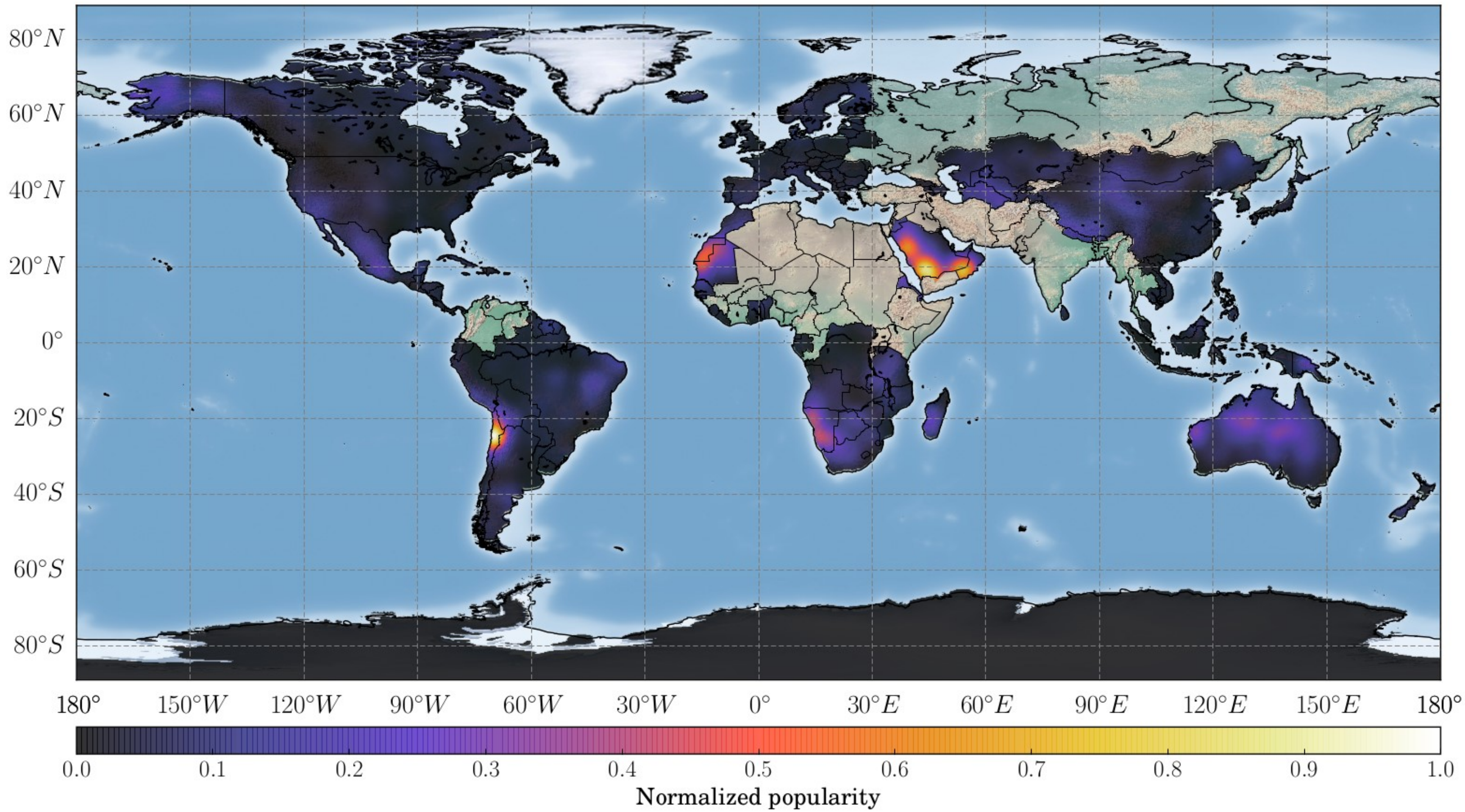

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- **Limitations and Future work**
- **Conclusions**

Conclusions

- A Markov-chain model to generate synthetic time series of cloud events has been presented.
- This cloud model was used in a computational tool to assess the availability, latency and cost of a network of OGS to serve LEO space optical communications.
- Results of the two scenarios analyzed:
  - The best locations identified include Dubai, Kitt Peak, Malargüe, Perth, Inuvik, Arequipa in the constrained scenario, and Saudi Arabia and Morocco in the unconstrained scenario.
  - Polar stations are no longer the ideal locations due to the high cloud probabilities at polar latitudes. Instead, the band of latitudes 20 – 40 deg contains the most attractive locations.
  - With just a 2x increase in data rate, optical technology matches the data volume downloaded when using RF.
  - However, latency of the network increases to 4 hours between passes, which might make an all-optical downlink approach unsuitable for latency sensitive applications (i.e., weather)

THANK YOU

Q&A

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BACK-UP SLIDES