ARCHITECTING THE GROUND SEGMENT OF AN OPTICAL SPACE COMMUNICATION NETWORK

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March 7th 2016

IEEE Aerospace Conference 2016
Big Sky, Montana

Outline

- **Introduction and Motivation**
- **Research Objective**
- **Our approach**
  - Cloud model description
  - Network availability computation
  - Cost model description
- **Results**
  - Constrained scenario
  - Unconstrained scenario
- **Limitations and Future work**
- **Conclusions**

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Introduction

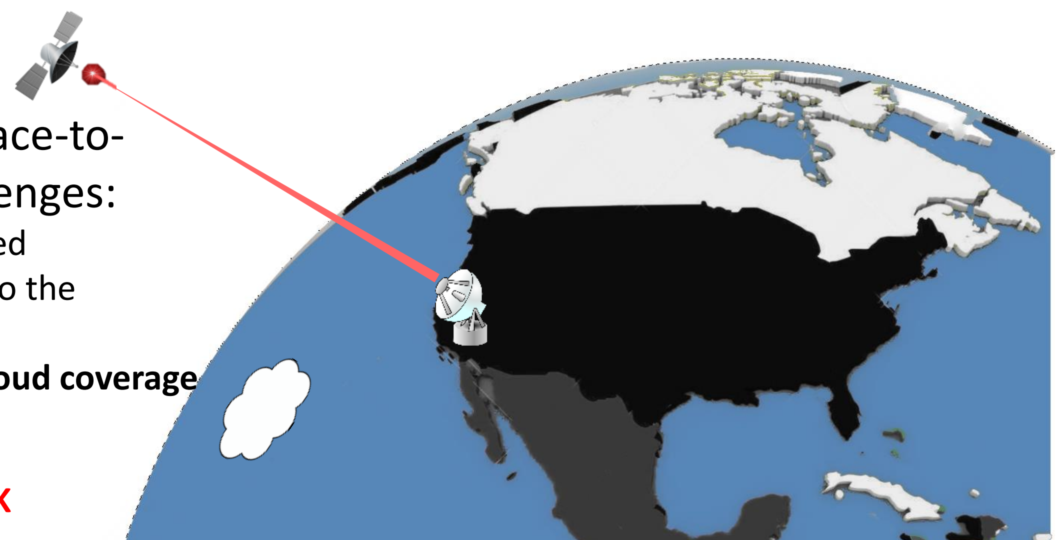
There are two main reasons that are driving the deployment of optical technology for space communications.

- Higher data volume request by users:
  - DESDyNI (cancelled) + NISAR = 60 Tb/day
  - 34 Tb/day current Space Network

- The current system is over-subscribed
  - High data rates provided by optical technology will alleviate the load of the Space Network

- Optical technology has other advantages
  - Low Size, Weight and Power
  - Optical spectrum is unlicensed

- Using optical technology for Space-to-ground links imposes new challenges:
  - New protocols need to be developed
  - Mitigation of link scintillation due to the atmospheric channel
  - **Mitigation of link outage due to cloud coverage**



AVAILABILITY OF THE NETWORK

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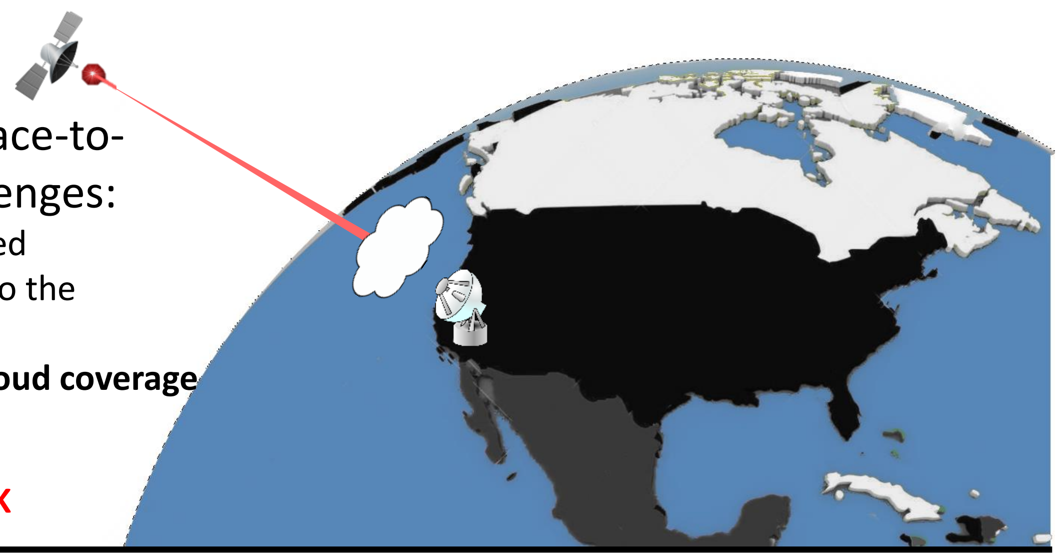

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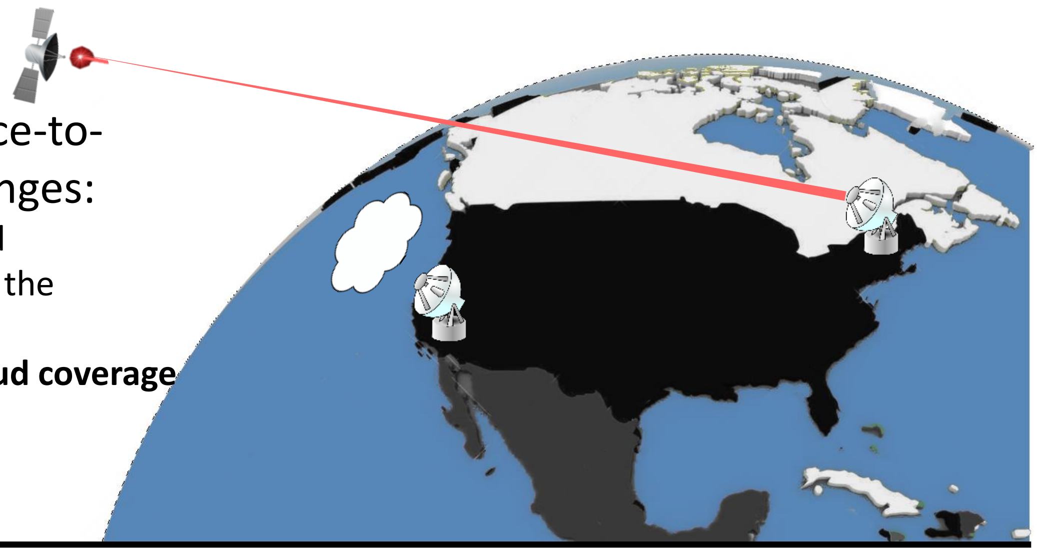

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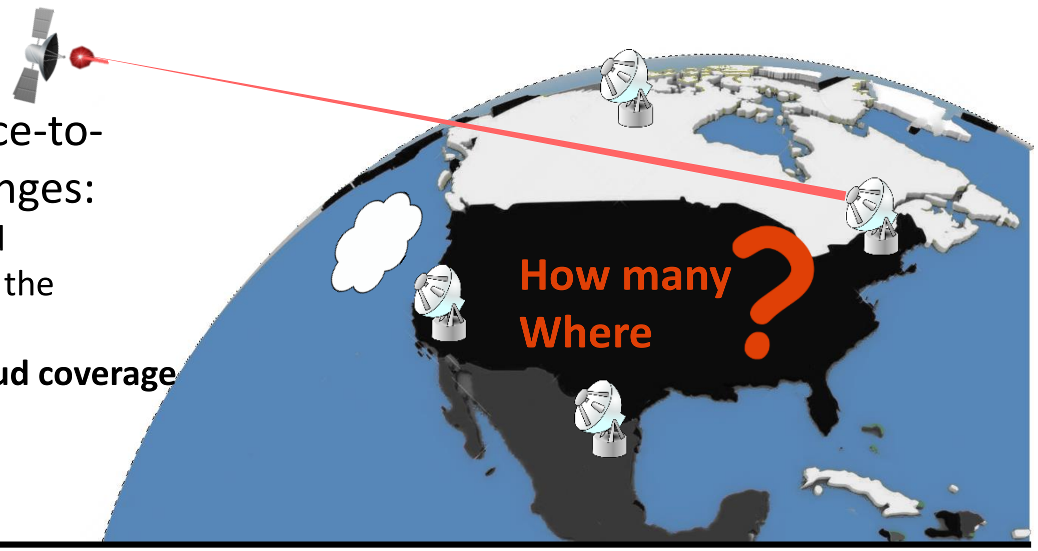

AVAILABILITY OF THE NETWORK

Motivation

Availability is mitigated using Ground Station site diversity:

- Requirements of a location to place an Optical Ground Station:
  - Low probability of link outage due to cloud coverage
  - High altitude site to reduce the optical air mass and reduce effects of atmospheric turbulence
  - Not isolated, at a reasonable distance of a communication network point of access
  - In a politically stable country
  - In case of using GEO relay satellites, preferably close to the equator to reduce the slant range

Near Earth Network

DSN

White Sands Complex

Other NASA/Partner assets

Astronomical Observatories

None of these facilities were originally built with the purpose of serving as an Optical Ground Station for high-throughput relay satellites.

- **Research question:** Do current assets offer the best conditions to place an Optical Ground Station or should new locations be considered?

Research Objective

To identify the optical ground segment architecture(s) that better address the needs of future near-Earth space missions **by**

1. Implementing a model that considers cloud coverage worldwide, and given the location of the ground stations evaluates its availability and cost

2. Exploring the architecture space defined by combinations of ground stations, presence of relay satellites in GEO and presence of ISL among them

using an adaptive genetic algorithm.

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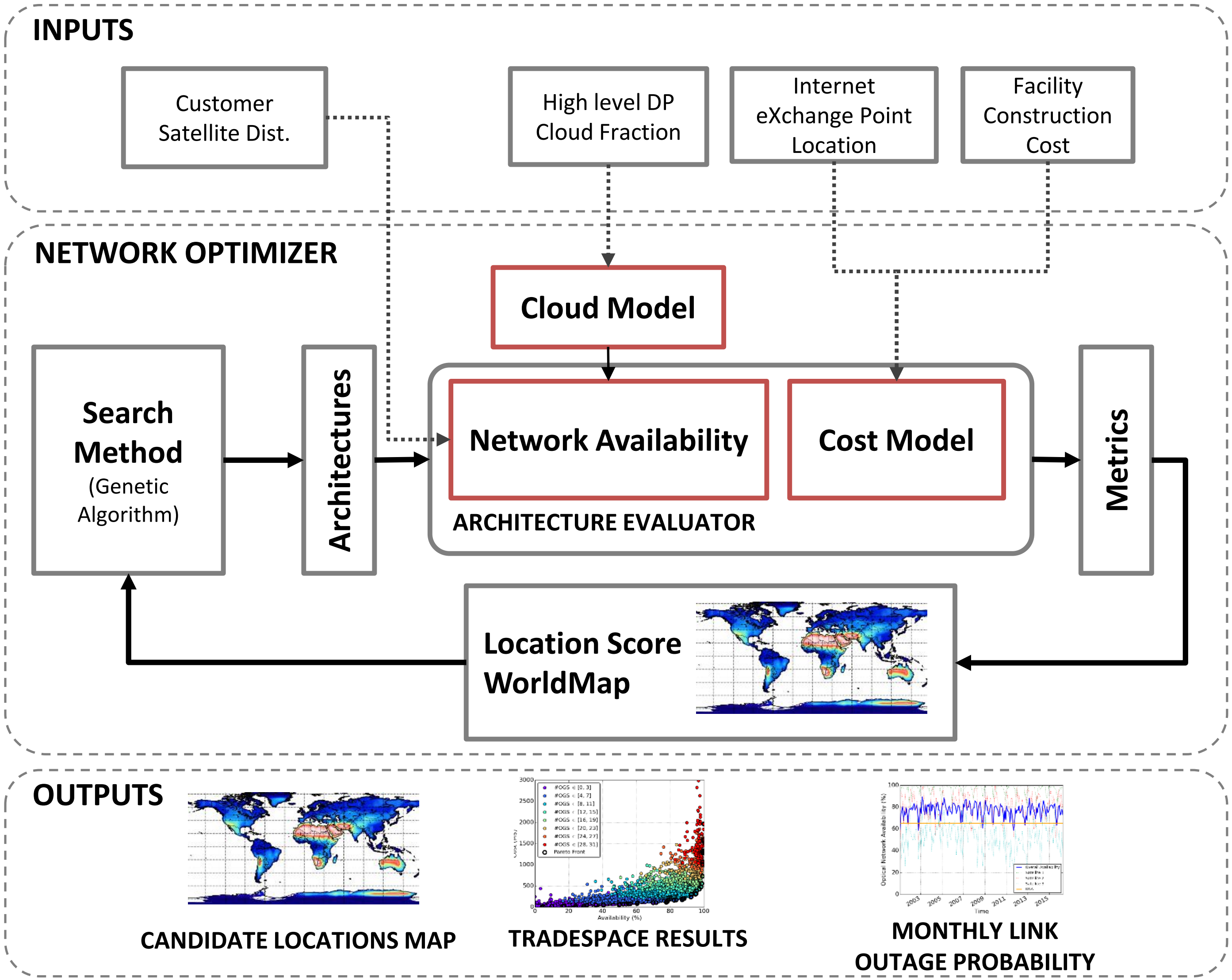
Overall picture



Cloud Model

Simulation Approach (Image data ~ 45 min)

Data extracted from cloud masks of weather satellites (MeteoSat, GOES, MTSAT)

- High accuracy of cloud link outage probability
- Not suitable for unconstrained tradespace exploration (high volume of data)

Analytical Approach

- Estimates the Link Outage Probability by using the monthly cloud fraction. (L3 Product of MODIS)
- Only marginal probabilities on each point (lat, lon) are available. (No correlation information)

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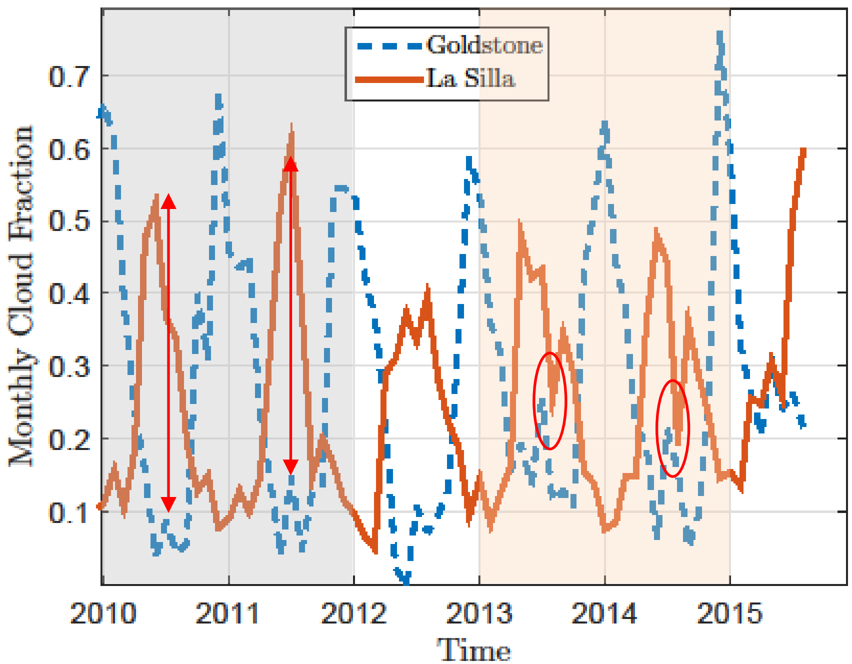
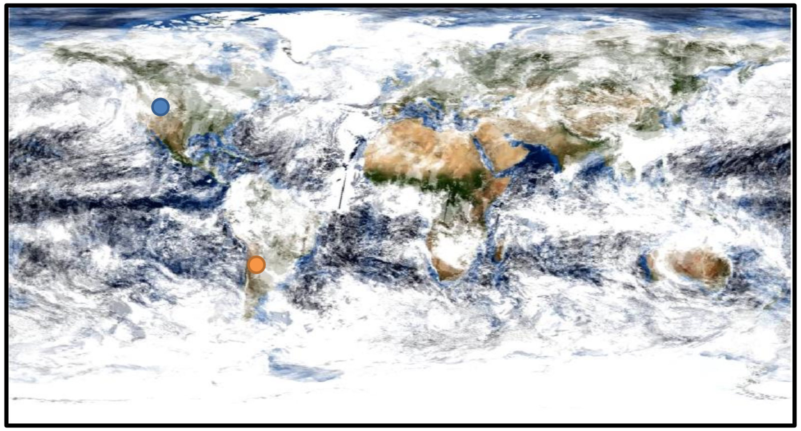


Image credit: Marc Sanchez



Correlation among different Optical GS:

- Temporal correlation (seasons)
  - Monthly data during 15 years of data from MODIS

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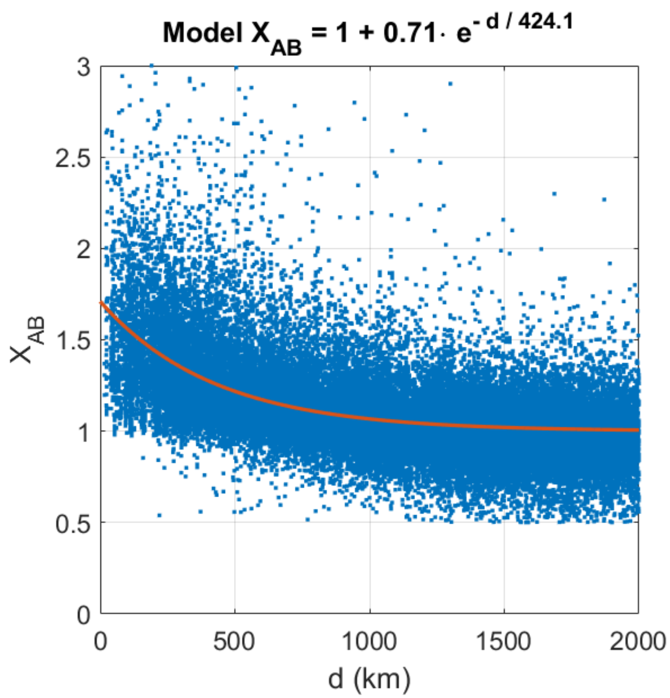
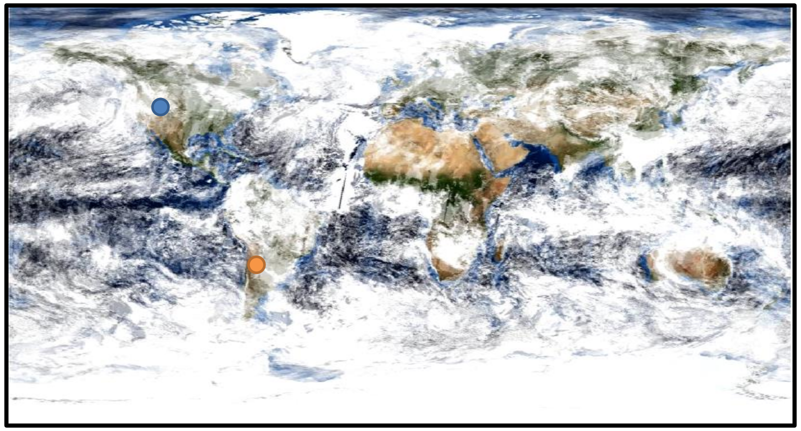




Correlation among different Optical GS

- Temporal correlation (seasons)
  - Monthly data during 15 years of data from MODIS
- Spatial correlation of cloud fraction:
  - Use of dependence index, as defined in [21]

$$P(C(A) \cap C(B)) = \chi_{AB} P\big(C(A)\big) P(C(B))$$

  - Reproduced the analysis in [21] using 700 ground stations across the globe.
  - Similar results (d_0 = 424 vs $d_0 \in$ *[200,400]km)*

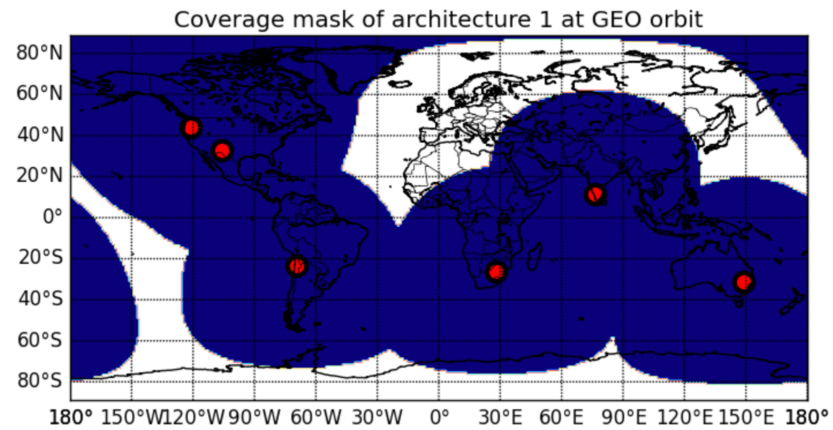
[21] P. Garcia, A. Benarroch, and J. M. Riera, "Spatial distribution of cloud cover," International Journal of Satellite Communications and Networking, vol. 26, no. 2, pp. 141–155, 2008.

Computing the network availability

Network availability computation process

Example: 6 optical GS + 3 relay satellites without ISL

1. Compute line of sight mask for each GS
   - On a 1° gridded sphere at altitude h
   - Taking into account elevation mask



$$M_{gs_i} = \{P = (\lambda(P), l(P)) | \epsilon_P \geq \epsilon_{min}\}$$

$$\epsilon(P) = \arccos\left(\frac{\sin\gamma}{\sqrt{1 + \left(\frac{R_E}{R_E + h}\right)^2 - 2\frac{R_E}{R_E + h}\cos\gamma}}\right)$$

$$\gamma = \sin\lambda(P)\sin\lambda(GS) + \cos\lambda(P)\cos\lambda(GS)\cos(l(P) - l(GS))$$

Computing the network availability

Network availability computation process

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   – Using the dependence index for correlated GS

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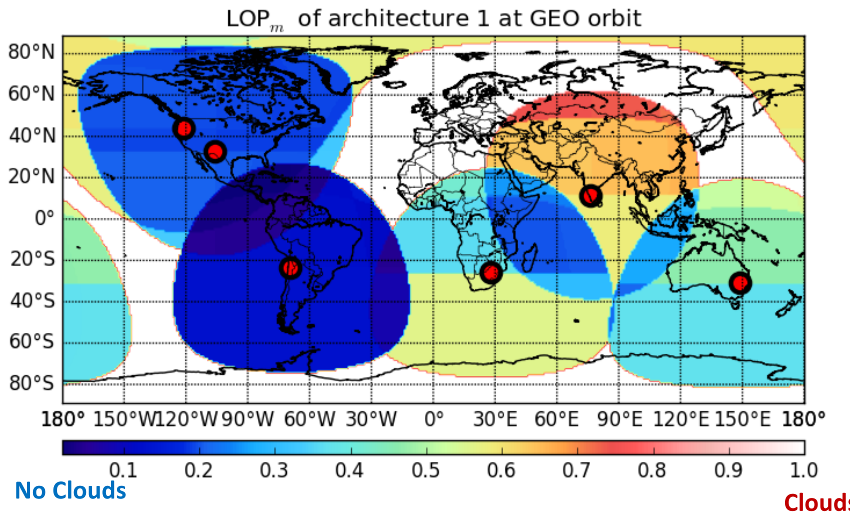

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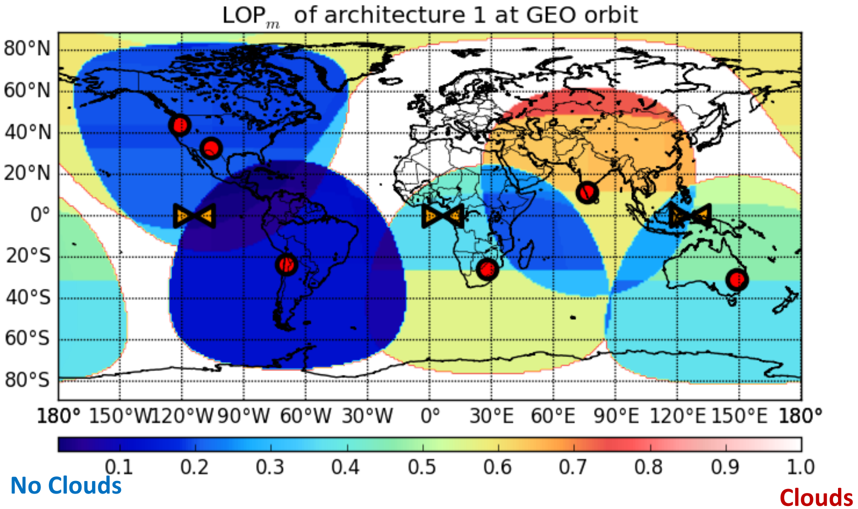
   - Formulated as a mathematical program
   - Locate 3 relay satellites in GEO (similar to current TDRSS)



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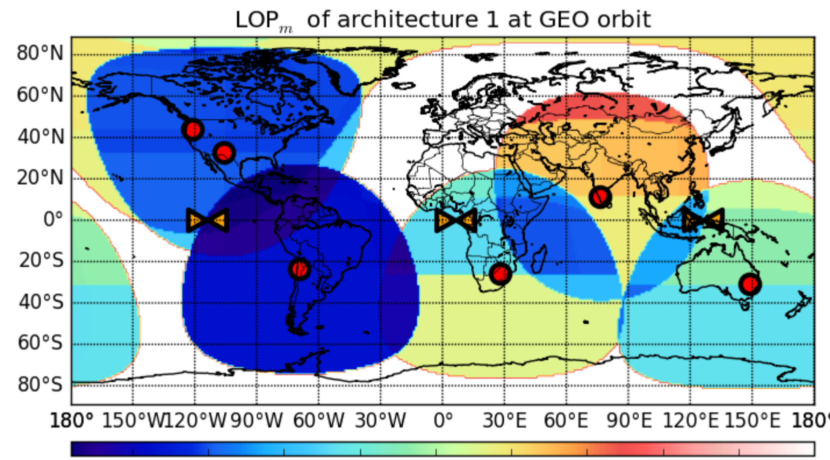
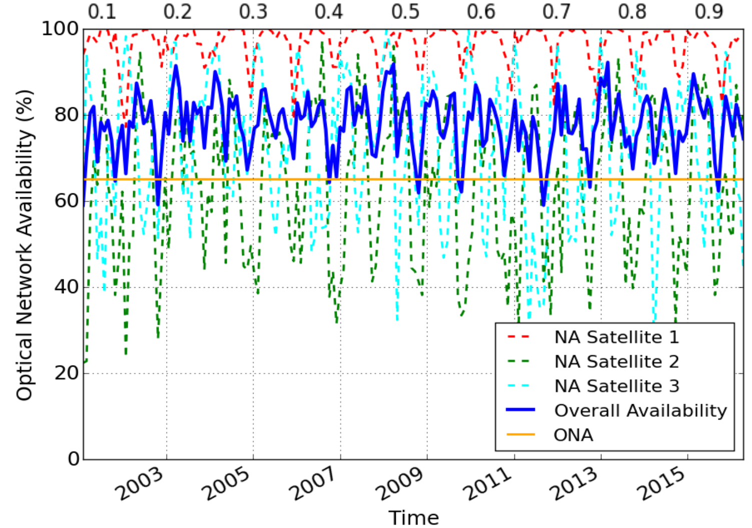
   - Locate 3 relay satellites in GEO (similar to current TDRSS)
4. Compute Optical Network Availability
   - Probability that there are no GS available for a satellite to downlink data at a given time.
   - Different formulae for GEO, LEO and presence of Inter-Satellite Links



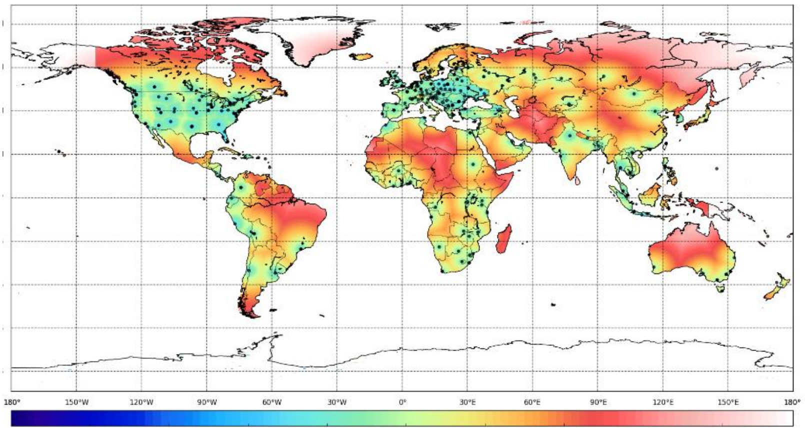


Cost Model

Parametric cost model based on:

- Ground Station location **[F(GS)]**
- Optical telescope diameter **[D]**
- Distance to transport network AP **[d_{IXP}]**

- Non-recurring + Recurring costs
- Lifecycle cost is computed assuming a 20 year horizon.



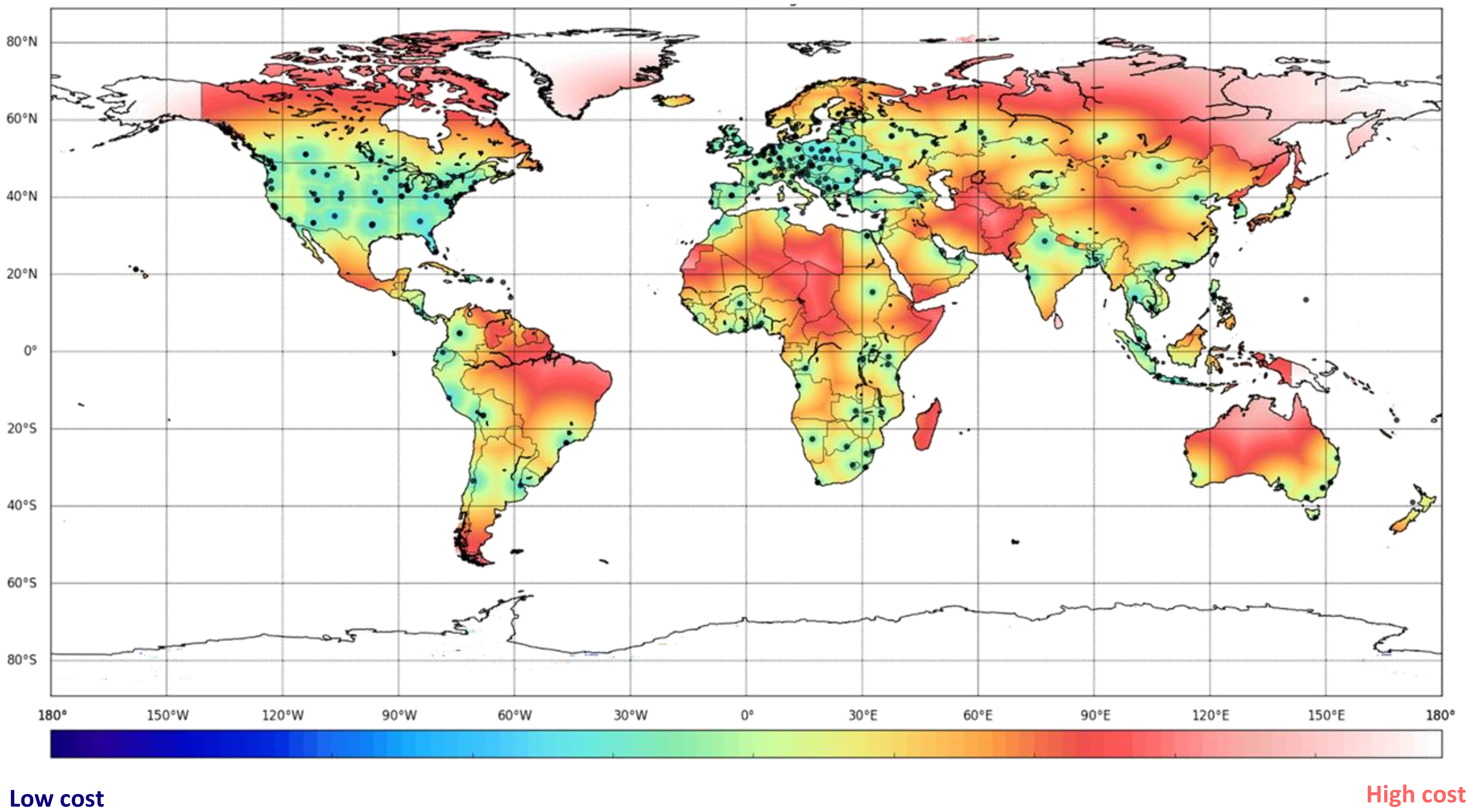
$$C_0(GS) = \boldsymbol{F(GS)}\Big(\underbrace{\mathrm{A_{gs}U_c}}_{\text{Construction Cost}} + \underbrace{\mathrm{k_{WAN}} \cdot \boldsymbol{d_{IXP}}}_{\text{Lay Fiber Cost}}\Big) + \underbrace{\mathrm{k_{tel}}\boldsymbol{D}^{2.7}}_{\text{Telescope Cost}}$$

$$C_t(GS) = \Big(\underbrace{\alpha_{WAN}}_{\text{WAN Service Fees}} + \underbrace{\alpha_{\mathrm{MO}}\mathrm{A_{gs}U_c}\boldsymbol{F(GS)}}_{\text{Maintenance \& Operations}}\Big)$$

$$C_{TOTAL} = \sum_{GS}\left[C_0(GS) + \sum_{t=1}^{20}\frac{C_t(GS)}{(1+r_t)^t}\right]$$

k	Name	Units	Ref.
A_{gs}	Area Ground Station	m^2	[22]
U_{gs}	Cost Ground Station	$\$/m^2$	[22]
k_{tel}	Cost of telescope	$	[23]
α_{WAN}	Fee WAN service	$	[24]
k_{WAN}	Cost WAN construc.	$/km	[25]
α_{MO}	% of cost for M&O	Adim.	[22]
r_t	Discount rate	Adim.	[22]

Cost Model


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
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150°E
180°
Low cost
High cost

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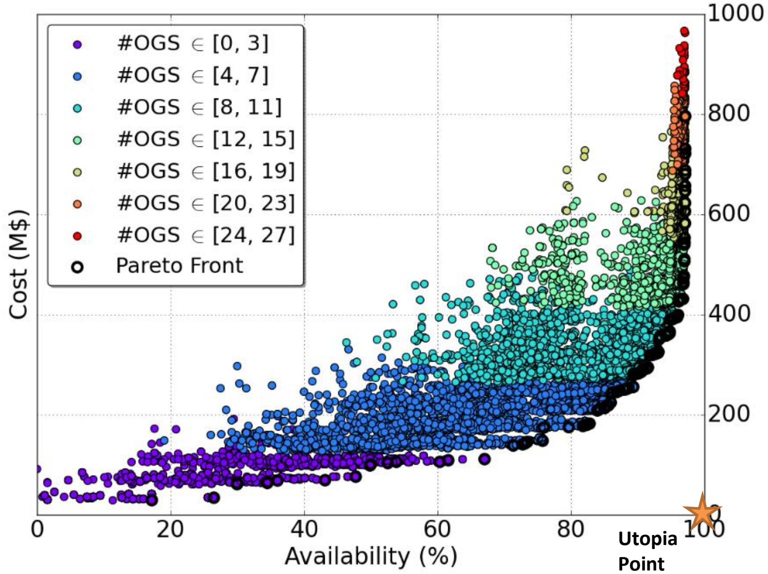
Results – GEO relay satellites

No Inter Satellite Link between relay satellites



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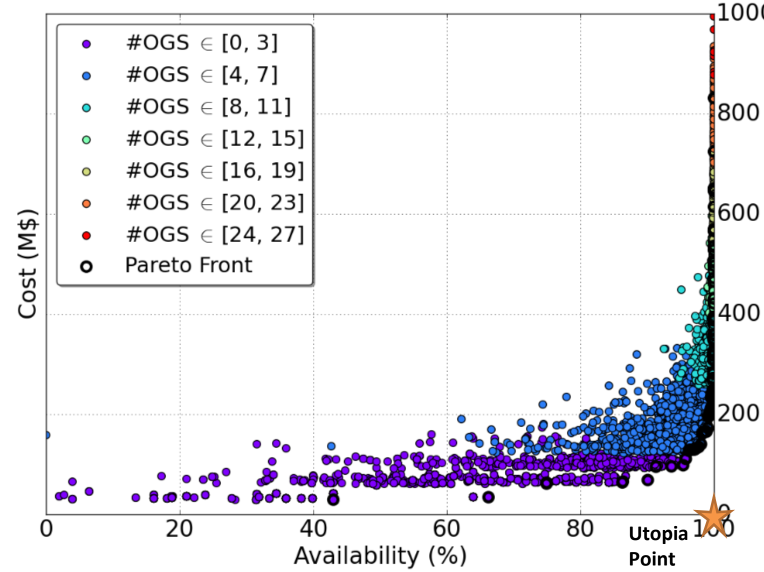
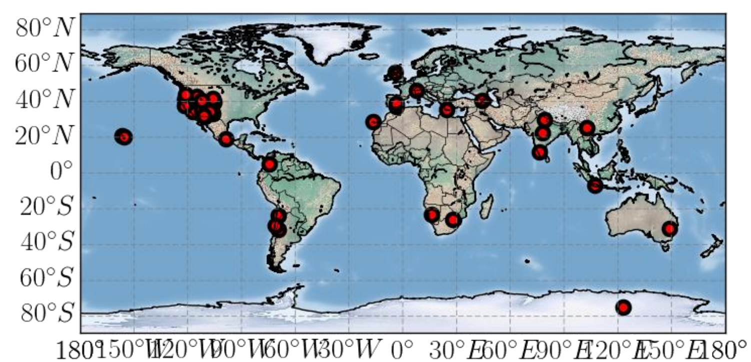
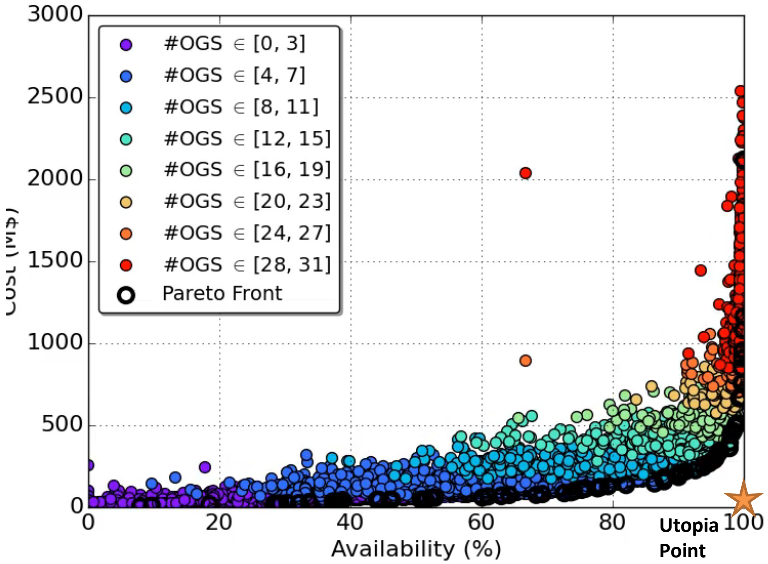


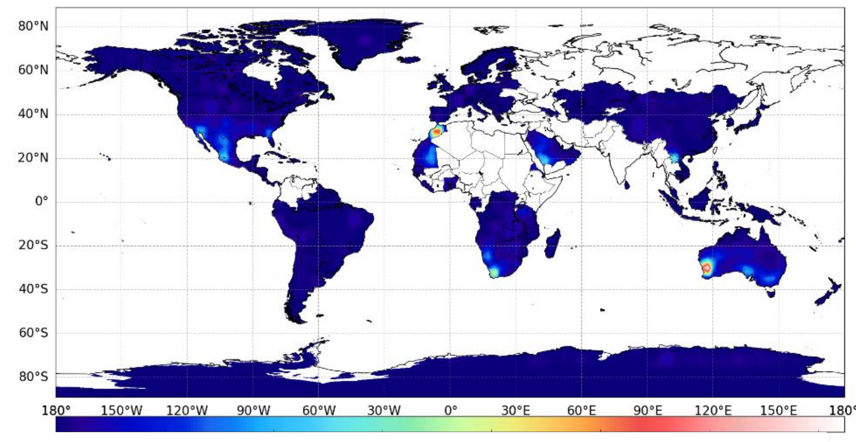
- Maximum availability without ISL is 95%, whereas using ISL 99% can be reached.
- For an availability of 90% without using ISL we need 7 GS whereas for an architecture with ISL only 3 are needed.
- Most popular locations include La Silla in Chile, HESS in Namibia and Aryabhatta Research in India.



Candidate ground station locations

Results – Unconstrained Optimization

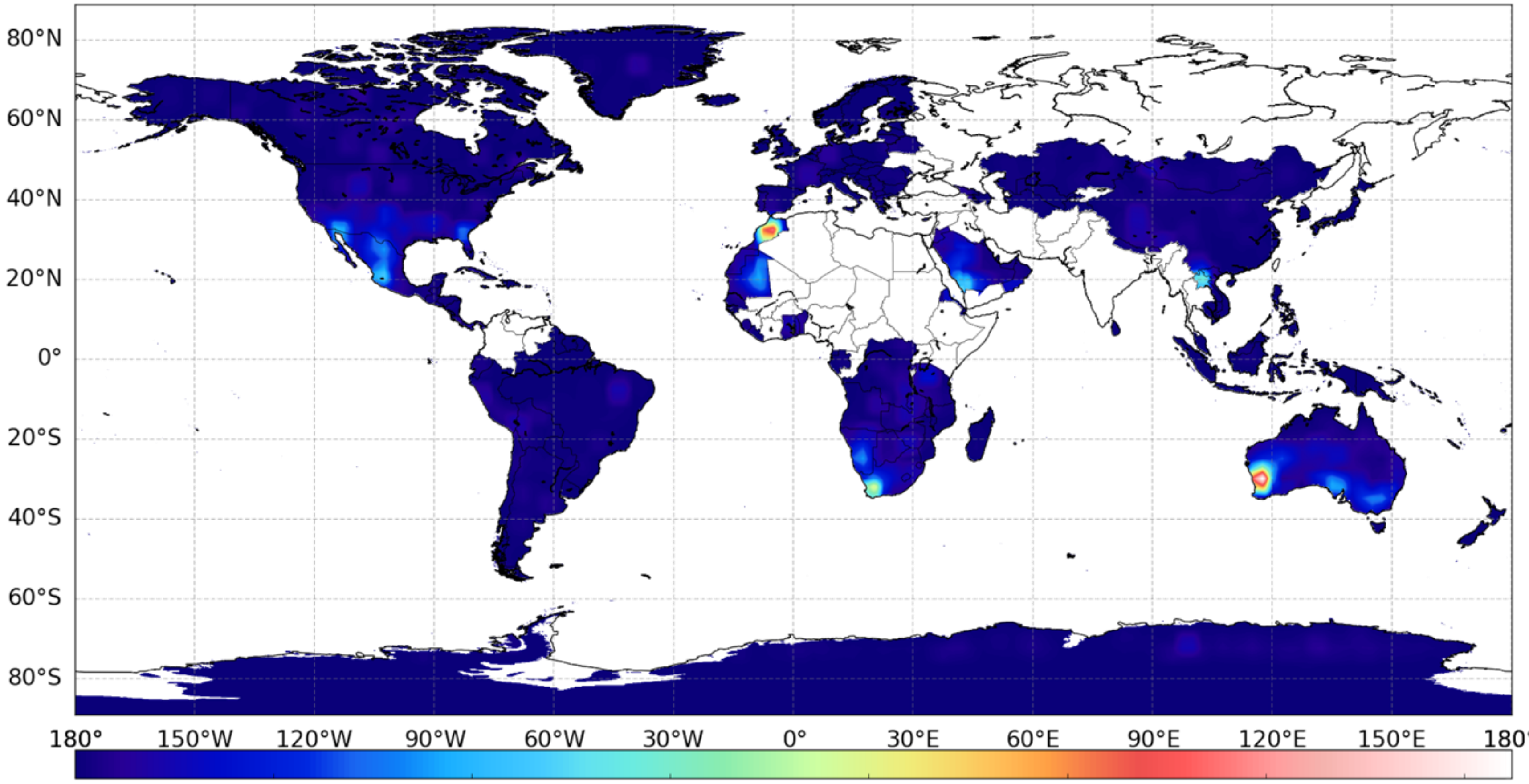




- The algorithm converges in 25 iterations to the Pareto optima for the GEO-no-ISL case study.
- 2,500,000 architectures evaluated
- 90% availability achieved with 6 GS. Similar results than in the OLSG study (NASA-2010)

- Most popular locations include West Coast of US, SouthWest and East Australia, South Africa and Namibia.
- New locations have been identified as compared to those considered previous literature: Saudi Arabia, North/Middle of Mexico, Morocco, North of Laos

Results – Unconstrained Optimization



Low score candidates

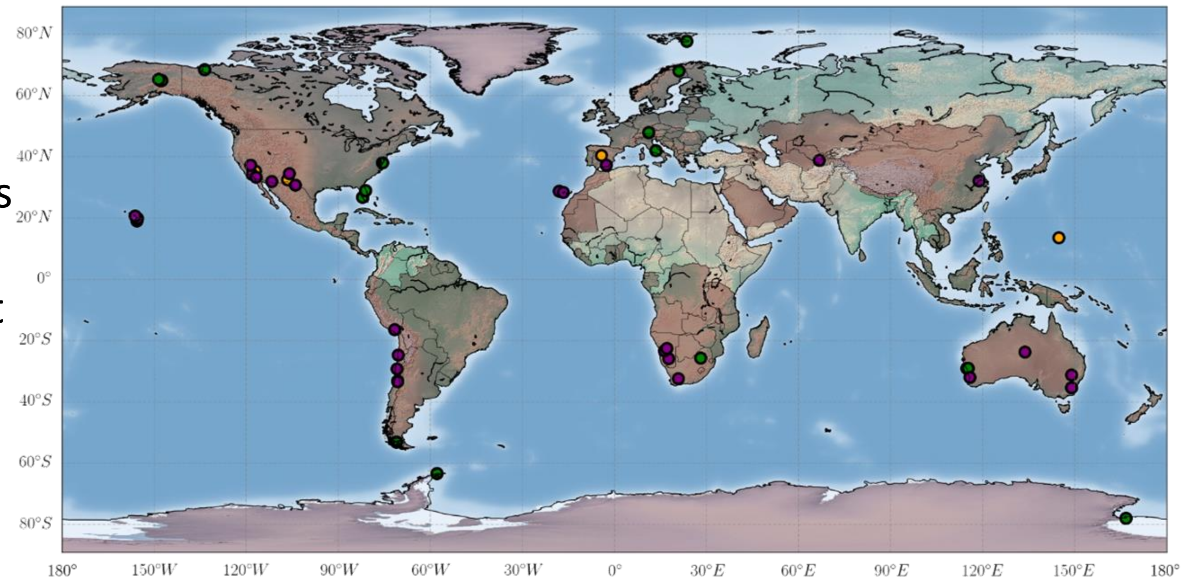
High score candidates

Results – Unconstrained Optimization

Comparison of Unconstrained Optimization with Existing Locations

Four different scenarios were considered:

- Use only **NEN** facilities
- Use **all NASA** owned facilities from NEN, DSN, and SN
- Use **observatories** from a list proposed by NASA in OLSG.
- **Unconstrained optimization** in politically stable countries



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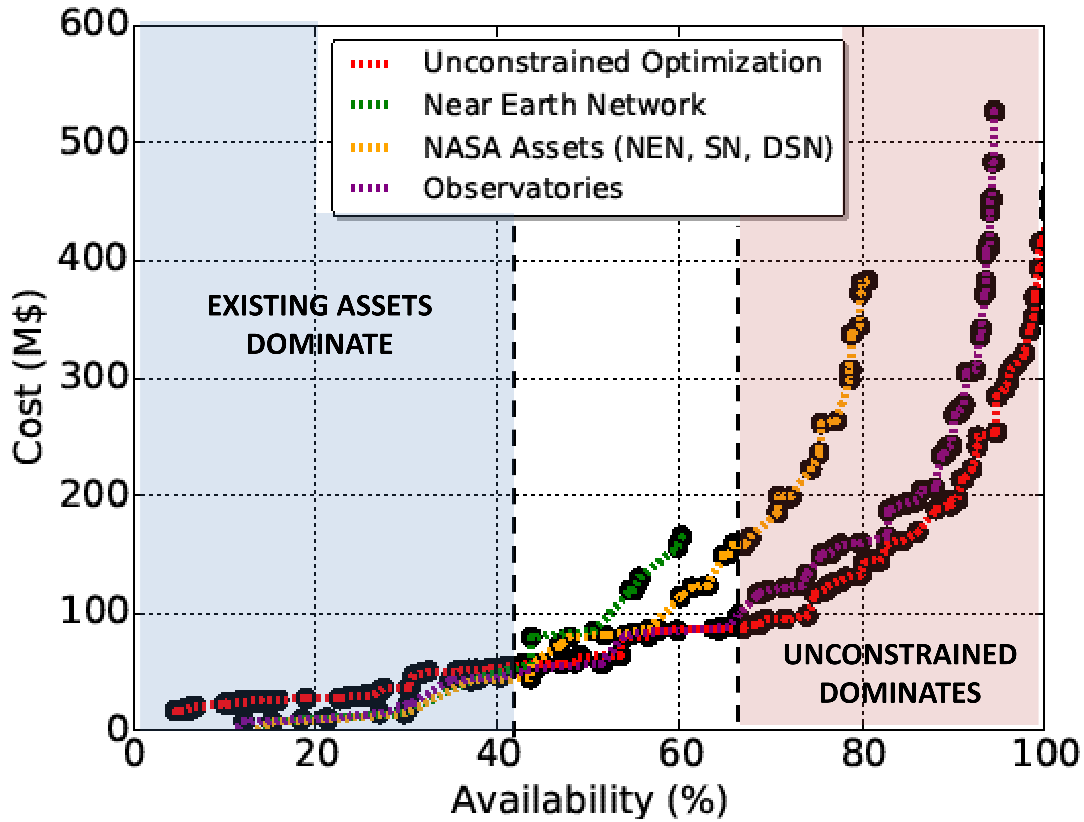
Different regions can be distinguished in the graph:

- For low cost, low availability using existing facilities dominates
- For high availability, new locations should be used



PRELIMINARY RESULTS. NEED TO VALIDATE THEM

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Limitations and Future Work

Cloud Model

- Cloud coverage effects in a temporal scale lower than a month are not modeled (i.e.: day-night effects, jet stream)
- Only 2 ground stations can be correlated simultaneously
- Locations cannot be negatively correlated

Working in a more complex formulation for the cloud model that solves these issues

Cost Model

- Difficult to have a cost model generic enough for the whole globe
- A lot of variability on the cost of laying down fiber, as it depends on a lot of parameters

Conducting sensitivity analysis to understand de dependence of the results with the cost model parameters.

Availability

- Handovers between ground stations are not modeled and we assume they do not affect the availability of the network.

Others

- The spatial resolution of the satellite data does not allow to model particular spot with exceptional conditions (i.e.: peak of a mountain)

Conclusions

- A computational tool to assess the performance and cost of a network of OGS for space optical communications has been presented.
- The tool uses a cloud model based on a high level data product that measures the cloud fraction, and USAF costing information and distance to the transport network access point for the cost model.
- Several studies have been conducted:
  - Using a constrained set of astronomical observatories as candidate locations, the best locations have been identified as La Silla (Chile), H.E.S.S. (Namibia) and Aryabhatta Research (India).
  - Using unconstrained optimization new locations have been identified (Morocco, Saudi Arabia, North of Mexico and North of Laos)
  - A comparison analysis of using assets proposed by NASA and the unconstrained scenario shows two regions. For low and medium availability using existing assets is beneficious whereas for very high availabilities exploring new locations is superior.
- There is work on progress to conduct:
  - Sensitivity analysis of the results to the cost model parameters.
  - Improvement to the cloud model that capture more realistically the spatial correlation among ground stations.

THANK YOU

Q&A

contact address : portillo@mit.edu

References (III/III)

[21] 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.

[22] Department of Defense. (2015) The DoD Facilities Pricing Guide.

[23] H. P. **Stahl**, G. Holmes Rowell, G. Reese, and A. Byberg. (2004) “Multivariable parametric cost model for ground based telescopes,” vol. 5497, pp. 173–180.

[24] Federal Aquisition Service, U.S. General Services Administration (2007), “NetworkX Unit Pricer”,

[25] Office of the Assistant Secretary for Research and Technology, U.S. Department of Transportation. Unit cost entries for fiber optic cable installation.

BACK-UP SLIDES

Previous Work

- Previous work closest to this work focuses on:
  - Uses fixed sets of candidate location
  - Does not provide a cost model and uses the number of ground stations as a proxy

Author	Deep Space	GEO	LEO	Location Ground Stations	Evaluated Tradespace Size (#) ↓	Candidate OGS Location (#)	Perf. Metric	Cost Model	Link Outage Approach	Optimization Methodology
Perlot	No	Yes	No	Europe	Small (1)	Single Point	Availability	No	Analytic	Single Point
Piazzola	No	Yes	No	N. America	Small (1)	Single Point	Data Volume	No	Image Data	Single Point
Poulenard	No	Yes	No	Europe	Small (4)	Fixed (25)	Availability	Backhaul	Image Data	Hand Picked
Tamayaka	No	No	Yes	Japan	Small (6)	Fixed (8)	Availability	No	Analytic	Hand Picked
Poulenard	No	No	Yes	Europe	Small (11)	Fixed (10)	Data Volume	No	Analytic	Hand Picked
Link	Yes	No	No	N. America	Small (512)	Fixed (12)	Availability	No	Image Data	Hand Picked
Fuchs	No	Yes	No	Europe	Medium(10^3)	Fixed (66)	Availability	No	Image Data	Custom Algorithm
OLSG	Yes	Yes	Yes	N. America	Medium (10^4)	Fixed (14)	Availability	Yes	Image Data	Full Enumeration
Wojcik	Yes	No	No	Worldwide	Medium (10^5)	Fixed (30)	Availability	No	Image Data	Custom Algorithm
This work	No	Yes	Yes	Worldwide	Big (10^7)	Unconstrained	Availability	Yes	Analytic	Adaptive Genetic Algorithm

Politically Unstable Countries

- Two options were considered: Ban certain countries or apply a risk penalization term to the cost metric.
- We opted for the second option. 42 countries have been banned from our second analysis due to political instabilities
- Banning criteria:
  - Lowest 20% scoring countries attending to the "*Political Stability and Absence of Violence / Terrorism*" indicator from the WorldBank "Worldwide Governance Indicators"

Country	Mín. Prct. Rank
Syrian Arab Republic	0.0
Central African Republic	0.5
Sudan	1.0
Yemen	1.5
Somalia	1.9
Iraq	2.4
Afghanistan	2.9
Pakistan	3.4
Sudan	3.9
Libyan Arab Jamahiriya	4.4
Congo	4.9

Country	Mín. Prct. Rank
Nigeria	5.3
Palestine	5.8
Ukraine	6.3
Mali	6.8
Lebanon	7.3
Egypt	7.8
Chad	8.3
Kenya	8.7
Niger	9.2
Ethiopia	9.7
Algeria	10.2

Country	Mín. Prct. Rank
Colombia	10.7
North Korea	11.2
Burma	11.7
Turkey	12.1
Cote d'Ivore	12.6
Israel	13.1
India	13.6
Cameroon	14.1
Bahrain	14.6
Tunisia	15.0
Guinea	15.5

Country	Mín. Prct. Rank
Uganda	16.0
Thailand	16.5
Iran (Islamic Republic of)	17.0
Burundi	17.5
Bangladesh	18.0
Russia	18.4
Venezuela	18.9
Burkina Faso	19.4
Kyrgyzstan	19.9

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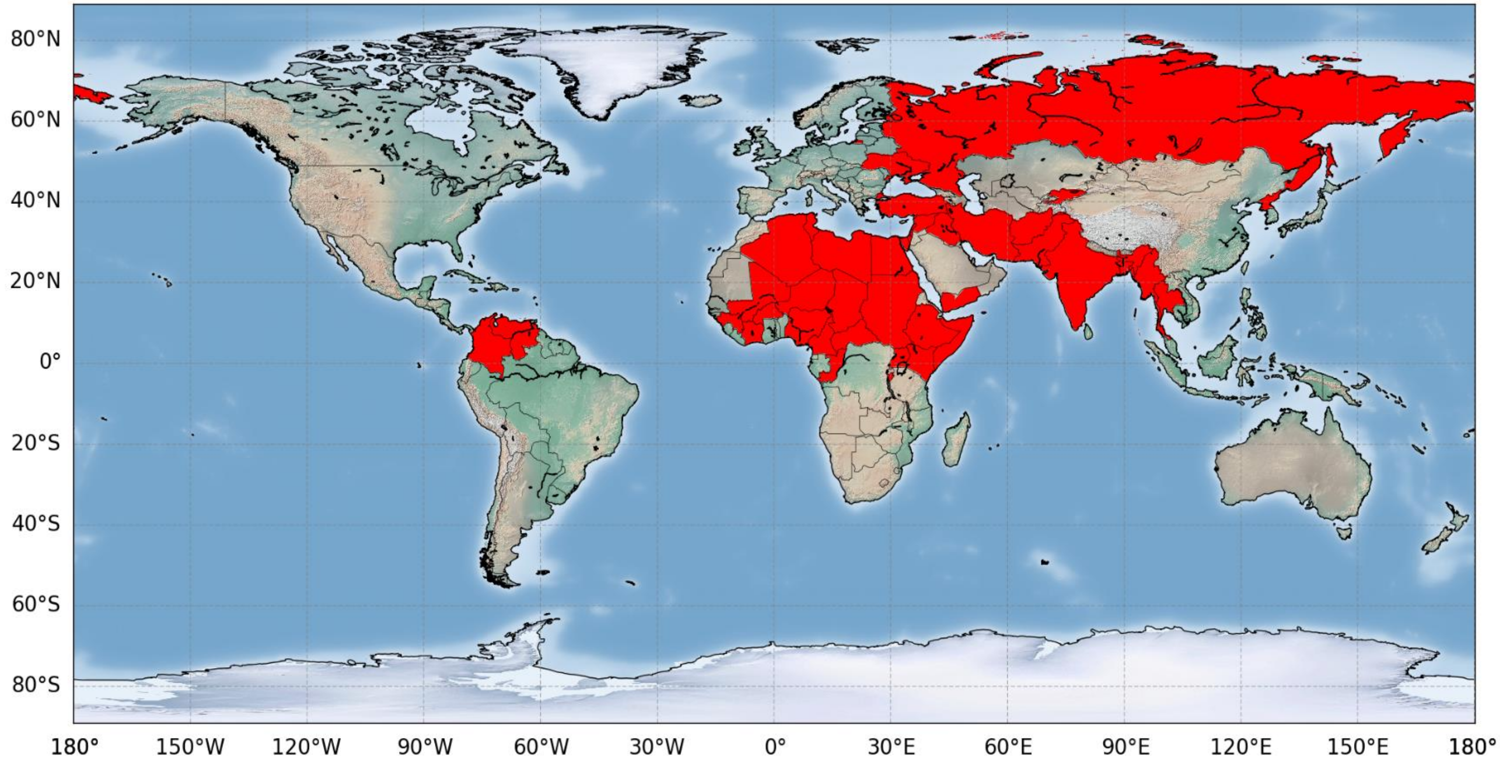
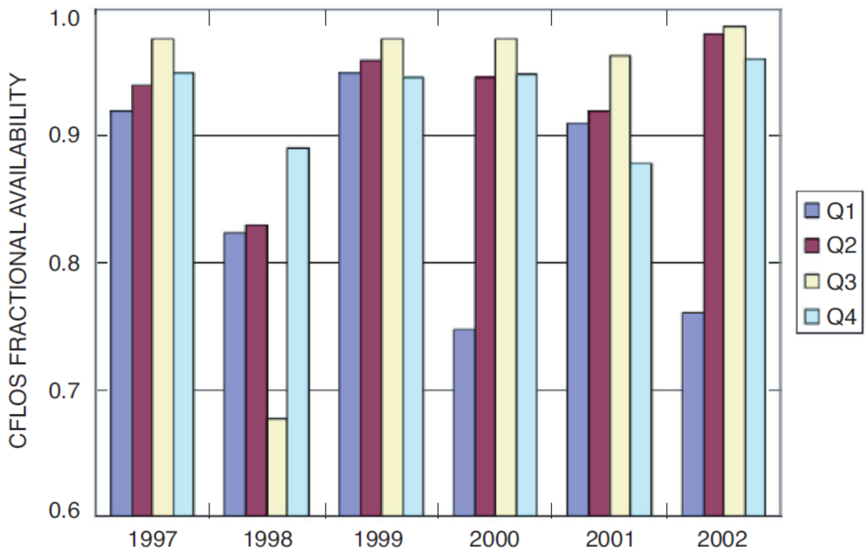


Comparison of availability with previous work

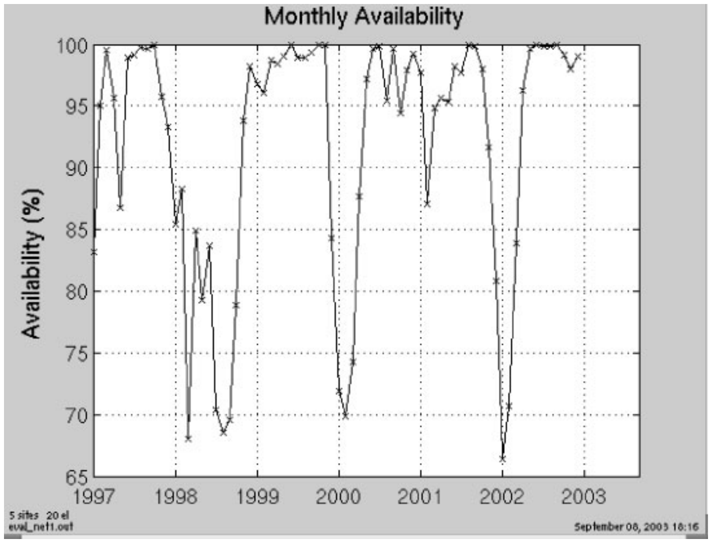
Author	Region	Years Imagery	# GS	# Sats	Optimal Locations	Reported Availability
Piazzola	USA	1997-2002	4	1	Goldstone (CA); Kitt Peak (AZ); McDonald Observatory (TX); and Mauna Kea (HI)	90.0 %
Poulenard	Europe + Middle East	2 years	5	1	**Egypt**, Yanbu (Saudi Arabia), Jeddah (Saudi Arabia), Gibraltar, Montpelier (France)	99.9 %
Tamayaka	Japan	2007	8	1	Tokyo, Sapporo, Fukuoka, Naha, Sendai, Osaka, Asahikawa, Kagoshima	95.0 %
Poulenard	Europe	2008	6	1	Marseille (France), Andorra, Rome (Italy), Nantes (France), Portugal, Greece	99.5 %
Poulenard	Europe	2012	4	1	Halfa (**Sudan**), Karak (Israel), Ouargla (**Algeria**), Garoowe (**Somalia**)	99.8 %
Link	N. America	1997-2002	5	1	Hawaii , Death Valley (CA), Tucson (AZ), Las Cruces (NM), Denver (CO)	90.0 %
Fuchs	Europe	2008-2012	12	1	Many locations.	100%
OLSG	N. America	2003	3	1	La Silla (Chile), Tenerife (Spain), White Sands (NM)	95.0 %
Wojcik	Worldwide	2003	6	3	Goldstone (CA) , Las Campanas (Chile), HESS (Namibia), Perth, Alice Spring and Mt Strombo (Australia)	91.0 %
Portillo	Worldwide	2002-2015	6	3	North Mexico, Namibia, Arabia Saudi, Morocco, West Australia, Laos	90.3 %

Comparison of availability with previous work

- Difficult to compare with previous work. Results from authors seem to have a high variability
- Using the 5 % quantile as the metric value might underestimate the probabilities.



Piazzola, *Deep-Space Optical Communications Link Availability and Data Volume*



Link, *Mitigating the Impact of Clouds on Optical Communications.*

- Both authors report availabilities of 90% in these cases but when using 5 % quantile the reported availability drops to 70 %.