State of the Art: Lasercom Systems Engineering and Challenges

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KISS Workshop on Lasercom for Small Satellites

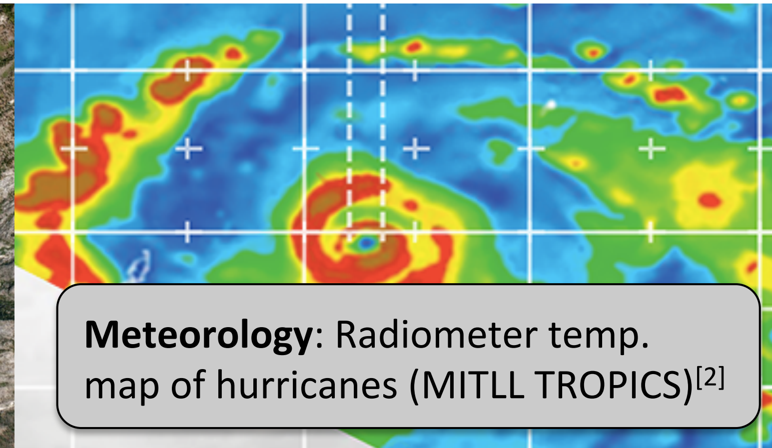
Outline

- Introduction
  - Motivation: Small Satellite Missions
  - Lasercom Advantages and Challenges
- Design of a Lasercom System
  - System Block Diagram
  - Link Performance Modeling
- Operations: Challenges and Opportunities
- Conclusion

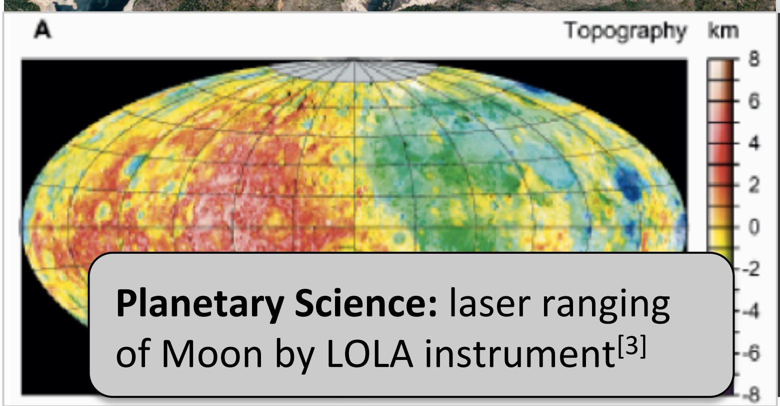
Missions can benefit from lasercom

Satellite data are used to provide insight into many problems, such as…

Local issues: Images of California draught (Planet Labs Inc.)[1]



Meteorology: Radiometer temp. map of hurricanes (MITLL TROPICS)[2]



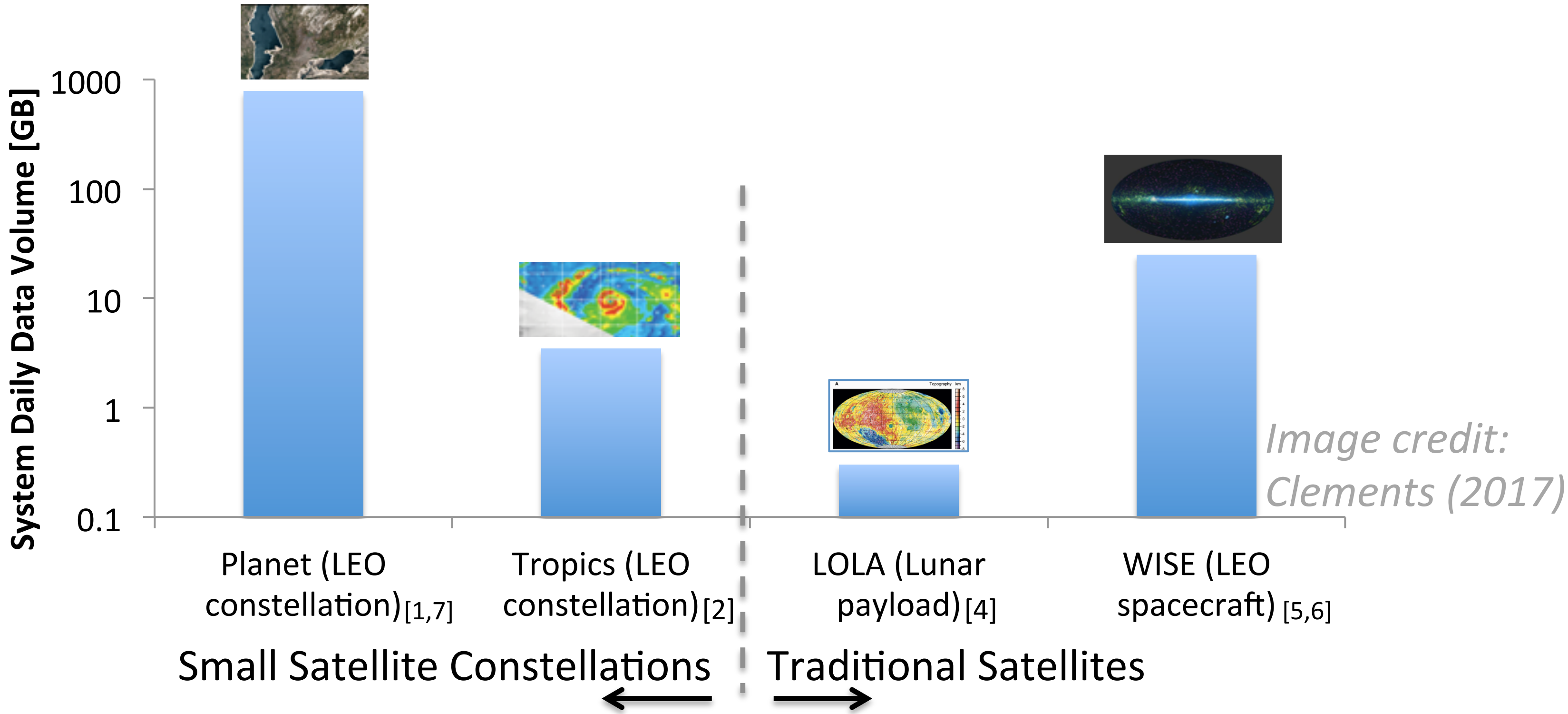
Planetary Science: laser ranging of Moon by LOLA instrument[3]

Astronomy: all-sky infrared survey (WISE satellite)[5,6]

Can <u>relaxed data constraints</u> enable new capabilities?

Utility for Small Satellite Missions

- Small satellites offer a cost-effective solution to global coverage w/ improved temporal resolution
- Data need metrics are: Volume of data downlinked, Timeliness/latency



Systems of small satellites can produce as much data as traditional satellites

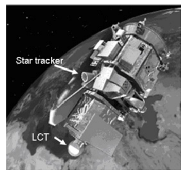
RF and Lasercom Advantages & Challenges

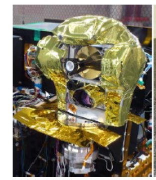
- Lasercom is more power-efficient than radio frequency (RF)
  - $P_{\text{received}} \propto \left(\frac{1}{\lambda}\right)^2$, where $P_{received}$ = received power, λ = wavelength

Objective/Metric	Radio Frequency	Lasercom
Data volume, **V**	Large transmit power and aperture size [8] (Selva, 2012)	**Higher downlink rates and lower SWAP (highly scalable for future needs)**
	Spectrum availability, large aperture ground station availability	**Cloud cover** hinders access; Addressed by diversity techniques but large networks not available yet
Age of Information, **AoI (latency)**	Depends on data volume	Depends on ability to crosslink, depends on clear line of sight (e.g., cloud cover for downlinking, and ground-station diversity)
Variance data vol. & AoI, **σ^2(V)** and **σ^2(AoI)**	**Link losses are more predictable**	Dependent on atmospheric conditions, variable cloud cover, communication architecture (e.g., diversity techniques, crosslinks, etc.)

SmallSat* Lasercom Missions

SmallSat Lasercom Tech. Demos





NFIRE-TerraSAR-X[9]
5.6 Gbps,
LEO crosslink

NFIRE LCT[10]
5.625 Gbps,
LEO downlink

LLCD[11]
622 Mbps
Lunar downlink

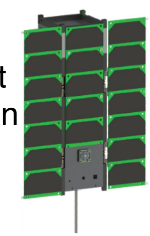
SOTA[12]
10 Mbps,
LEO downlink

OCSD[15]
NODE,[15] FLARE

2005 — 2010 — 2015 — Future

BRITE[13]
0.0115° pointing

MINXSS[14]
0.002° pointing, first flight of Blue Canyon wheels



Missions that Advance Supporting Tech.

Related: UAV lasercom:

Facebook Aquila[17]
Optical crosslinks between aircraft

Google Loon[18]
155 Mbps crosslink,
balloon lasercom system

*Defined SmallSat as <500 kg[19]

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System Block Diagram

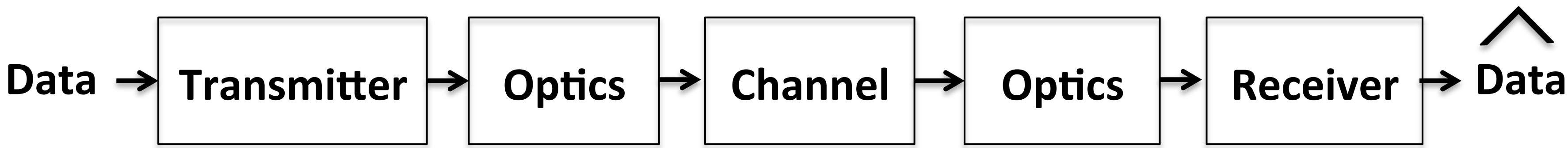
- Communication system block diagram:

Adapted from Figure 2, Caplan, David O. "Laser communication transmitter and receiver design." Journal of Optical and Fiber Communications Reports 4.4-5 (2007): 225-362.[20]

- Additional system considerations
  - Pointing control
  - Onboard memory
  - Mechanical/thermal subsystems
  - System with multiple transmitters/receivers

Link Performance Modeling

- Received power is a function of gains and losses throughout the system:



$$P_{\mathrm{Tx}} G_{Tx} L_{\mathrm{Tx}} L_{\mathrm{Tx.point.}} L_{FS} L_{\mathrm{atm}} G_{Rx} L_{\mathrm{Rx}} L_{\mathrm{Rx.point.}} \eta = P_{\mathrm{rx}}$$

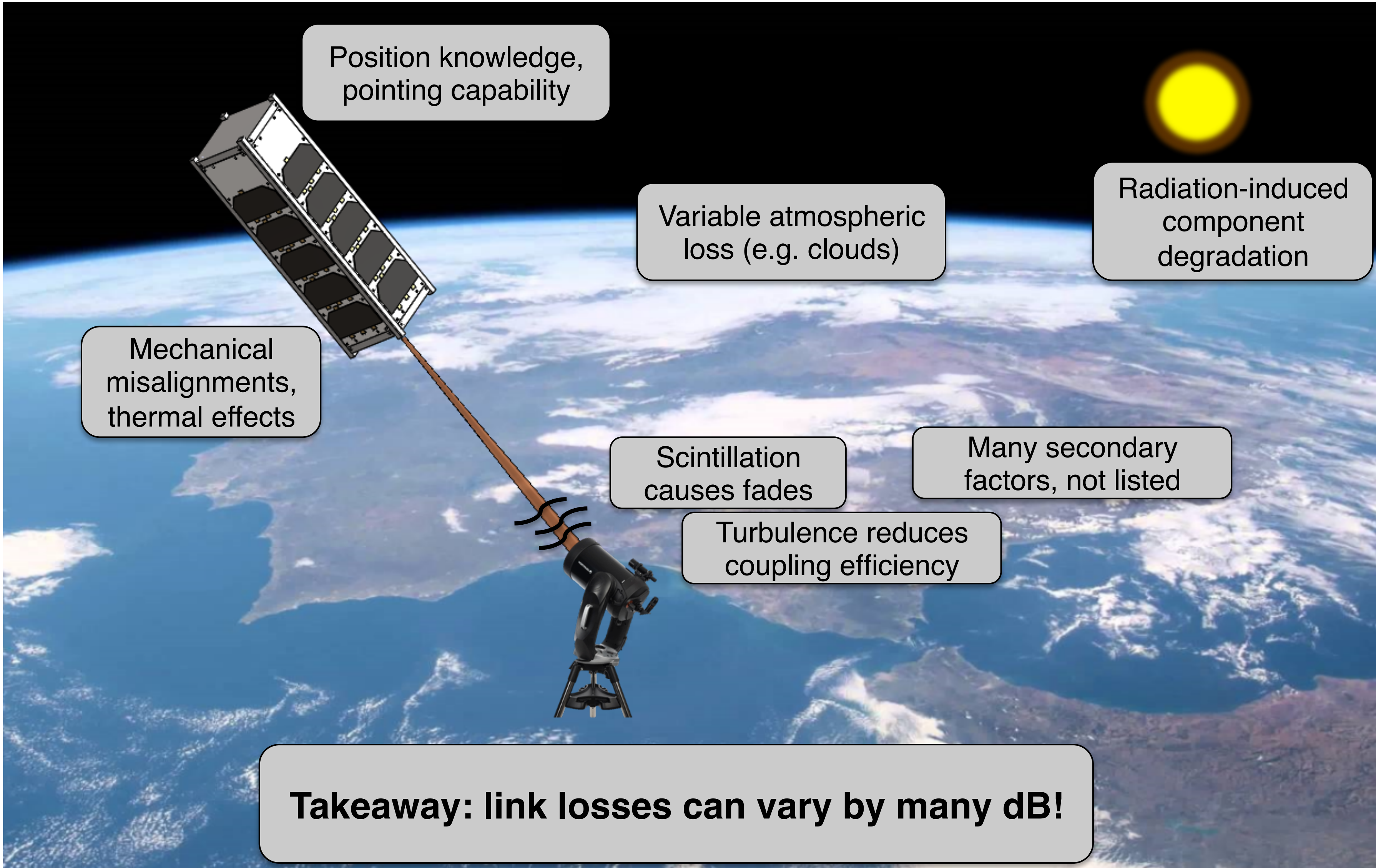
Aside: equations same as RF! →

$$G_{Tx} = \left(\frac{\pi D_{tx}}{\lambda}\right)^2 \qquad L_{FS} = \left(\frac{\lambda}{4\pi R}\right)^2 \qquad G_{Rx} = \left(\frac{\pi D_{\mathrm{rx}}}{\lambda}\right)^2$$

Data rate is proportional to P_{Rx}

Figure adapted from Figure 2, Caplan, David O. "Laser communication transmitter and receiver design." Journal of Optical and Fiber Communications Reports 4.4-5 (2007): 225-362.[20]

Performance Uncertainty Sources



Takeaway: link losses can vary by many dB!

Figure credit: Ziegler, Clements;
Adapted from slide 48, Caplan, "Introduction to Laser Communications"

Link Performance Modeling

Nominal Link Budget for NODE (LEO, CubeSat, downlink-only)

	NODE	Units
Datarate	43	Mbps
P_{tx}	-7.0	dBW
G_{tx}	69.6	dB
L_{tx}	-1.5	dB
$L_{freespace}$	-258.2	dB
L_{atm}	-1.0	dB
G_{rx}	114.7	dB
L_{rx}	-3.0	dB
P_{rx}	-78.0	dBW
P_{req}	-84.2	dBW
Margin	**6.2**	dB

Table from Clements et al. (2016)[15]

Alternative modeling approach estimates input uncertainties and creates CDFs of link margin

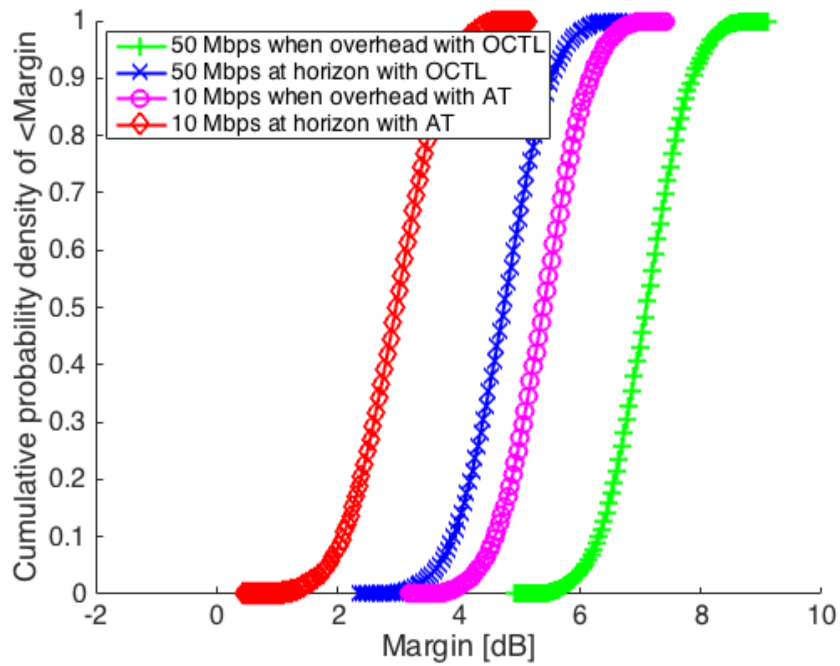


Figure from Clements, Cahoy (2017)[21]

Can model deterministically or through Monte Carlo analysis

E.g., for NODE (MIT CubeSat lasercom downlink payload in development for resource-constrained systems)

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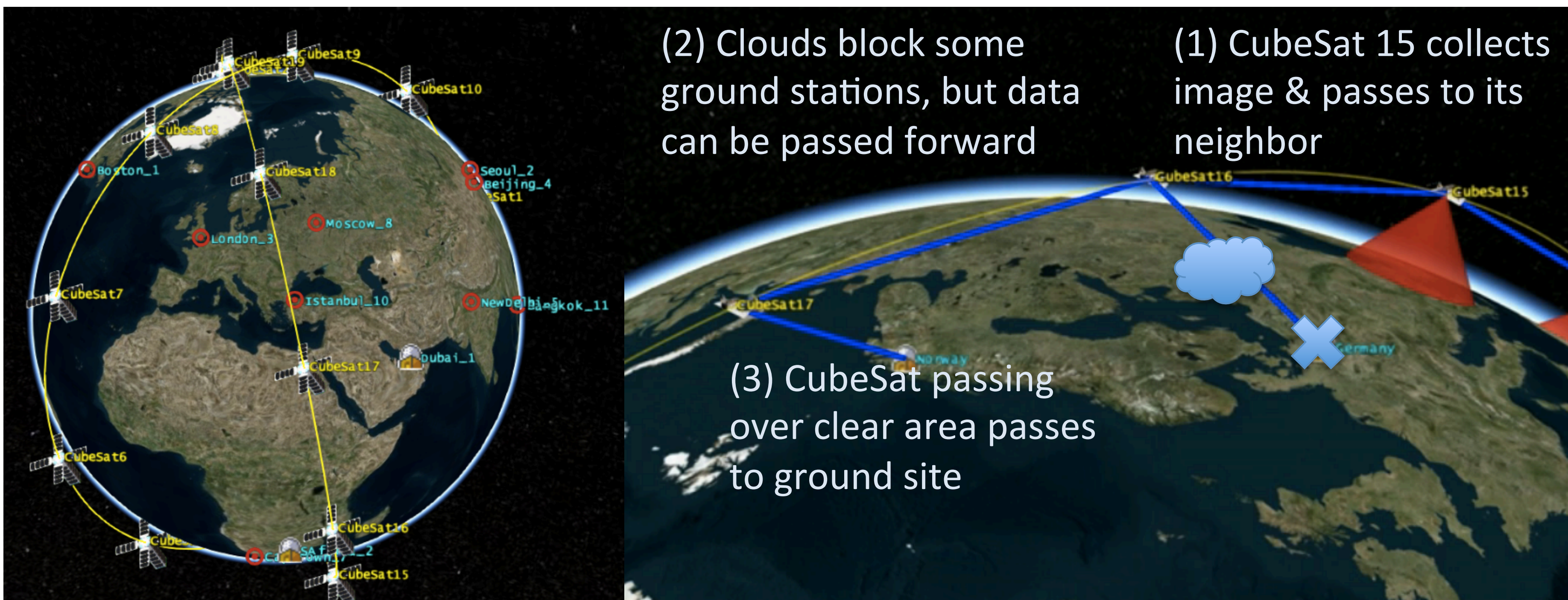
Constellation Opportunities

Problem: capacity saturation of ground stations for constellations of satellites with high datarate downlink needs

Solutions: (i) Many inexpensive ground terminals, (ii) Crosslinks



Visualization of Earth-observing small satellite mission using laser communication
Figure credit: A. Kennedy

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Conclusion

- Small satellite communications depend on data volume, timeliness (latency), and reliability
- Lasercom can provide high data capabilities with power- and SWAP-efficient designs
- Primary challenge is that it is a relatively new technology in the space environment
  - Capabilities have been demonstrated (e.g., LLCD, TeSAT, etc.).
  - Potential for improvement is significant BUT experience is currently limited and operational uncertainties remain

Bibliography

1. https://www.planet.com/gallery/lake-eleanor/
2. https://tropics.ll.mit.edu/CMS/tropics/Science-Objectives-and-Significance
3. Smith, David E., et al. "The lunar orbiter laser altimeter investigation on the lunar reconnaissance orbiter mission." *Space science reviews* 150.1-4 (2010): 209-241.
4. Neumann, G. A., et al. "Lunar Reconnaissance Orbiter Lunar Orbiter Laser Altimeter Reduced Data Record and Derived Products Software Interface Specification." *NASA Planetary Data Systems, LRO-L-LOLA-4-GRD-V1. 0, March* (2011).
5. https://www.nasa.gov/mission_pages/WISE/multimedia/gallery/gallery-index.html
6. Wright, Edward L., et al. "The Wide-field Infrared Survey Explorer (WISE): mission description and initial on-orbit performance." *The Astronomical Journal* 140.6 (2010): 1868.
7. Colton, Kyle, and Bryan Klofas. "Supporting the Flock: Building a Ground Station Network for Autonomy and Reliability." (2016).
8. Selva, Daniel, and David Krejci. "A survey and assessment of the capabilities of Cubesats for Earth observation." Acta Astronautica 74 (2012): 50-68.
9. Fields, Renny, et al. "NFIRE-to-TerraSAR-X laser communication results: satellite pointing, disturbances, and other attributes consistent with successful performance." SPIE Defense, Security, and Sensing. International Society for Optics and Photonics, 2009.
10. Fields, R., et al. "5.625 Gbps bidirectional laser communications measurements between the NFIRE satellite and an optical ground station." Space Optical Systems and Applications (ICSOS), 2011 International Conference on. IEEE, 2011.
11. Boroson, Don M., et al. "Overview and results of the lunar laser communication demonstration." SPIE LASE. International Society for Optics and Photonics, 2014.
12. Takenaka, Hideki, et al. "In-orbit verification of small optical transponder (SOTA): evaluation of satellite-to-ground laser communication links." SPIE LASE. International Society for Optics and Photonics, 2016.
13. Sarda, Karan, et al. "On-orbit performance of the bright target explorer (BRITE) nanosatellite astronomy constellation." (2014).
14. Mason, James P., et al. "Miniature X-Ray Solar Spectrometer: A Science-Oriented, University 3U CubeSat." Journal of Spacecraft and Rockets 53.2 (2016): 328-339.
15. Rose, Todd S., et al. "LEO to ground optical communications from a small satellite platform." SPIE LASE. International Society for Optics and Photonics, 2015.
16. Clements, Emily, et al. "Nanosatellite optical downlink experiment: design, simulation, and prototyping." Optical Engineering 55.11 (2016): 111610-111610.
17. D. Gershgorn, “Facebook will use these lasers to beam internet from the sky,” http://www.popsci.com/facebook-will-use-these-lasers-beaminternet-sky (2 July 2015).
18. C. Metz, “Google laser-beams the film real genius 60 miles between balloons.” http://www.wired.com/2016/02/google-shot-laser-60-milesjust-send-copy-real-genius/ (24 February 2016).
19. E. Buchen and D. DePasquale, “2014 Nano/Microsatellite Market Assessment,” SpaceWorks Enterprises, 2014, Inc.(SEI) Atlanta, Georgia, http://www.sei.aero/eng/papers/uploads/archive/SpaceWorks_Nano_Microsatellite_Market_Assessment_January_2014.pdf (29 August 2015).
20. Caplan, David O. "Laser communication transmitter and receiver design." Journal of Optical and Fiber Communications Reports 4.4-5 (2007): 225-362.
21. Clements, Emily, and Kerri Cahoy. "Probabilistic Methods for Nanosatellite Engineering: A Lasercom Case Study." 2017 AIAA SciTech Forum, Grapevine, TX. AIAA. January 2017.

Backup / from old talks

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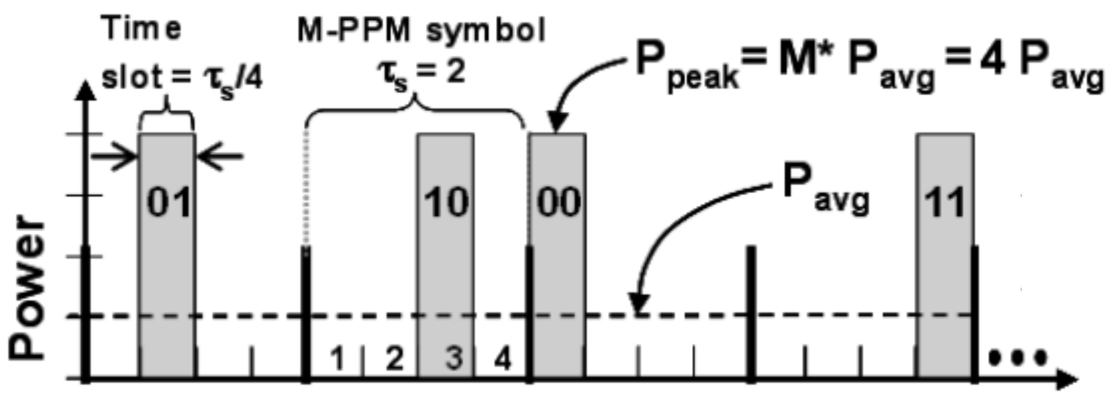
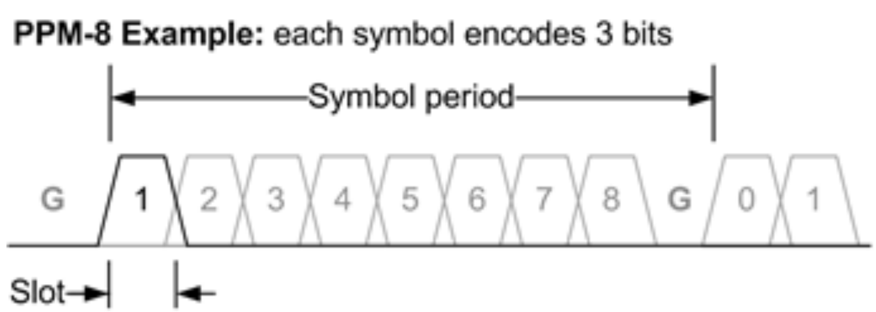
PPM Diagrams



Credit: *Laser Communication Transmitter and Receiver Design* by Dave Caplan



Credit: Ryan Kingsbury