We3C-1

Demonstration of a 40 Gbps Bi-directional Air-to-Ground Millimeter Wave Communication Link

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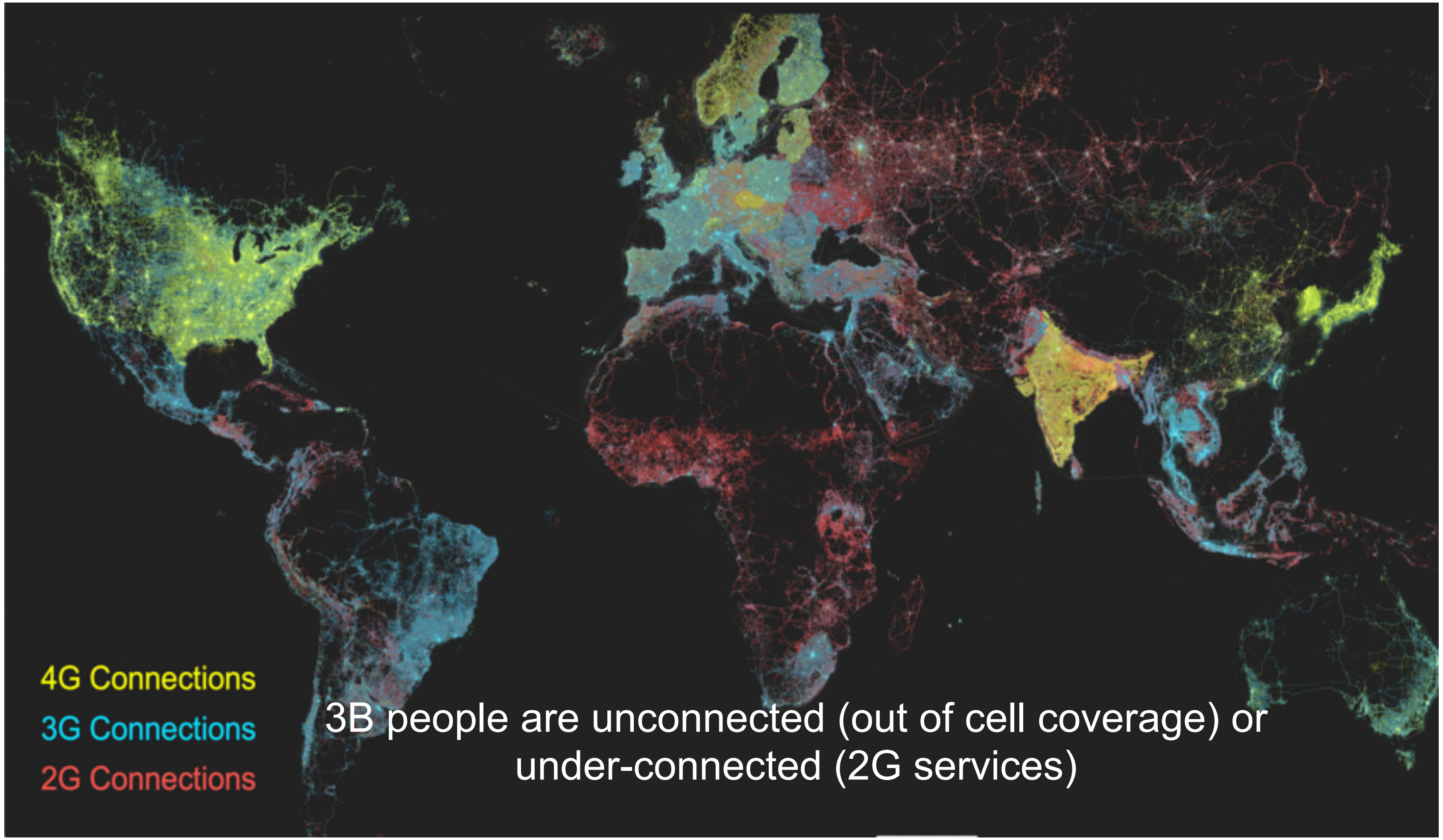
Outline

- Motivation and Introduction
- E-band HAPs Communication
- System Specifications and Architecture
- Flight Validation
- Quillayute Rain Test
- Conclusion

Motivation: Connect the Un-connected

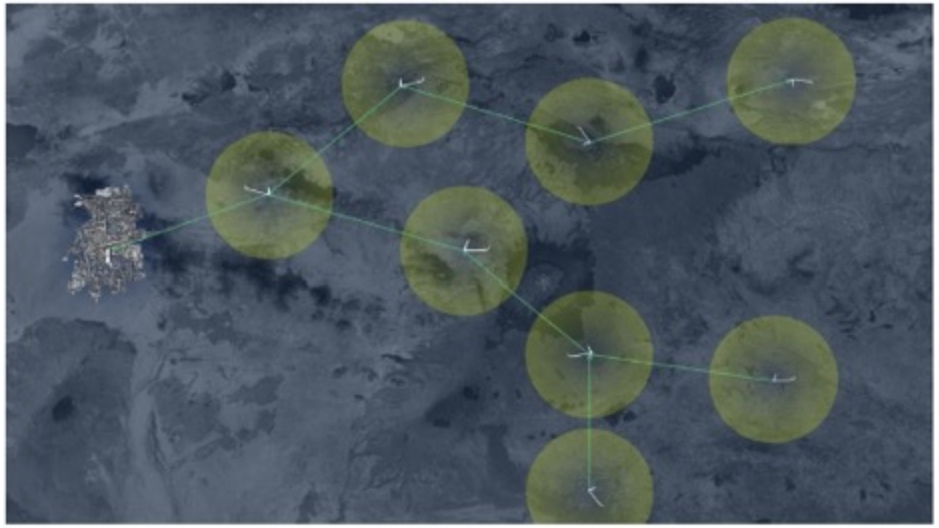


"The **digital divide** between the 12 lowest-income countries and rest of the world increased, as the rate of growth in internet users slowed more significantly in lower-income countries than other"

– *The Inclusive Internet Index 2019*

Sources: ITU broadband commission 2018 report and The Inclusive Internet Index 2019 Summary

High Altitude Platform (HAP) Internet Links



Aquila platform (Example UAV constraints):

- Solar-powered high altitude platform
- Altitude: 18 to 28km (morning/night)
- Coverage radius: up to 50km
- Dynamics: velocity up to 40m/s, 10° pitch/roll
- Position: 3km deviation from axis of coverage
- Energy: 3kWh over worst case 12hr period
- Overall cost of operation of the HAP network less than $20K/HAP/month

FBC payload solutions:

- **HAPiLink-P2P: 40 Gbps bi-directional at E-band**
- **HAPiLink-O: 100 Gbps bi-directional over FSO laser beam**
- **HAPiLink-P2MP: 4 Gbps bi-directional w/ phased array**

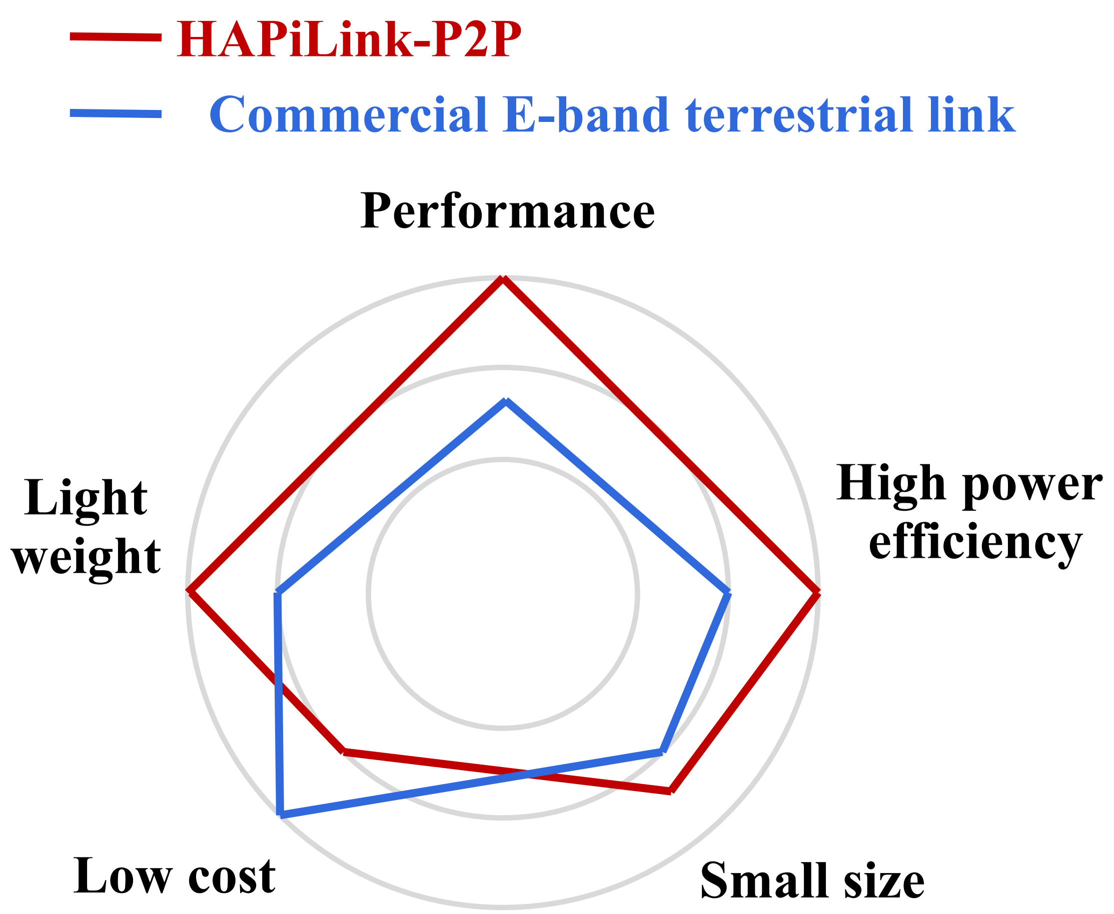
Why Millimeter-Wave?

- $G_t = \frac{4\pi A_e}{\lambda^2}$

- $FSPL = \left(\frac{4\pi d}{\lambda}\right)^2$

- $G_r = \frac{4\pi A_e}{\lambda^2}$

Design Challenges and Achievements



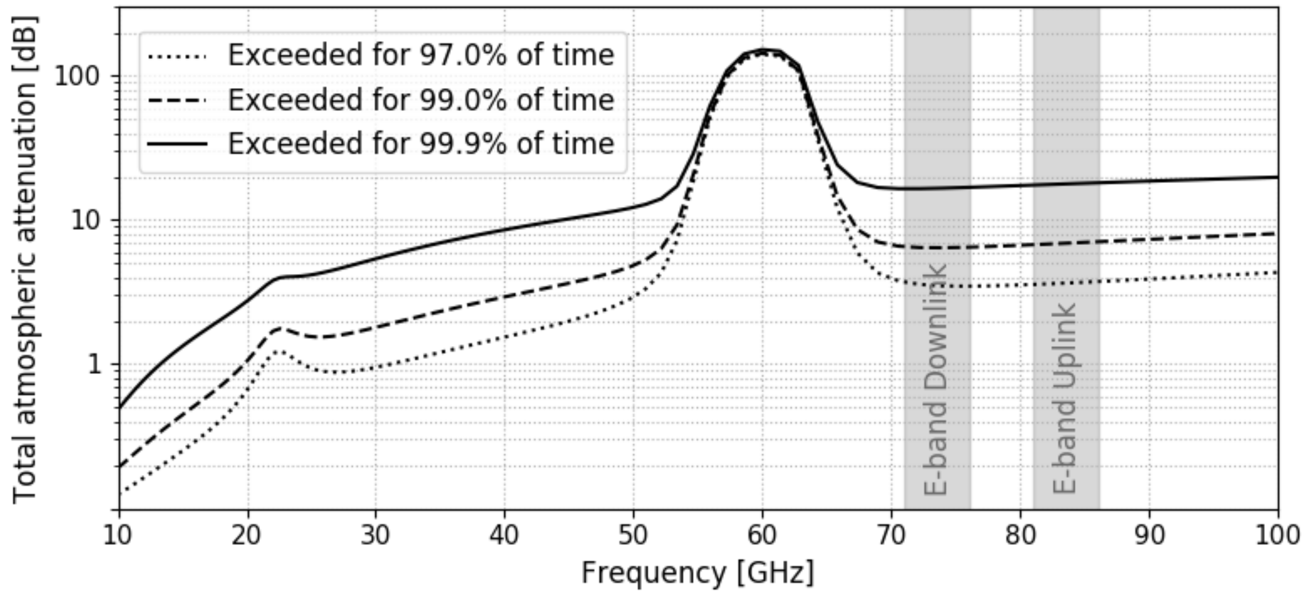
Parameter	Final Target Spec.	First Prototype
Total bandwidth used	10 GHz	71-76, 81-86GHz
Slant Range	6km – 30 km	7km and 12km flights 50km achievable
Elevation angle	35º to 70º	34º and 70º
Clear weather data rate	32 Gbps	40 Gbps up & down
Data rate in 8mm/hr of rain	10 Gbps	Spot checked the ITU model 618-12 for rain attenuation over an air-to-ground link
Data rate in 15mm/hr of rain	2 Gbps	
Airborne terminal DC power	< 140 Watts	247 Watts
Ground terminal DC power	< 500 Watts	865 Watts
Mass of the airborne terminal	< 6 kg	11.8 kg

Main goal of our 1st prototype: Maximize throughput, range & link availability

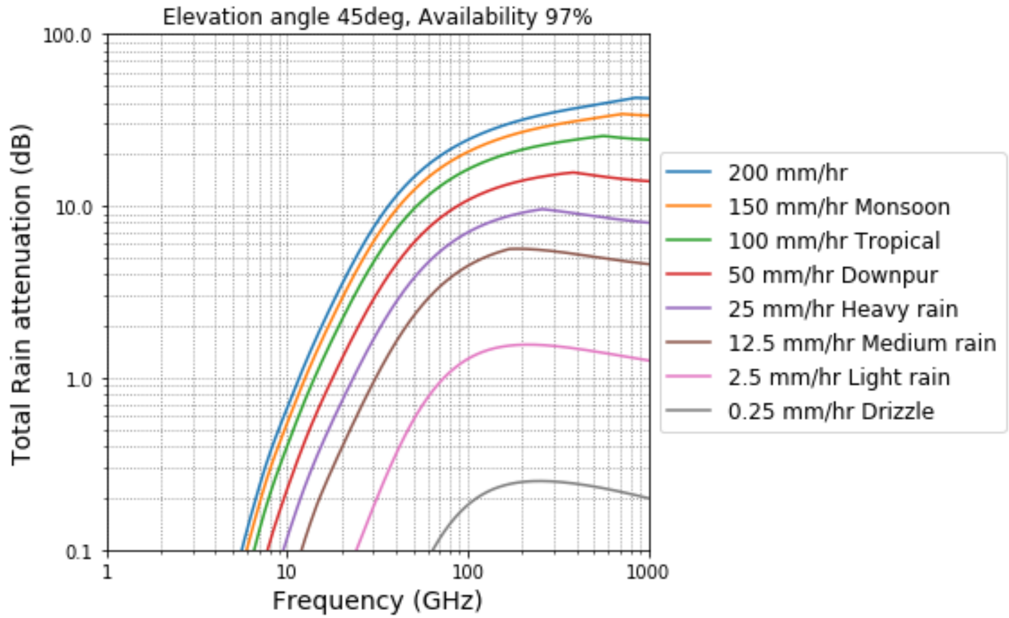
E-Band (71-86 GHz) Link

- **Abundant spectrum** – 15 GHz bandwidth, high throughput
- **Lightly restricted license** – quick, cost-effective but still interference protected
- **Robust weather resilience** to fog, dust, air turbulence – compared to 60 GHz and laser optics
- **Air-to-ground 'above the weather'– atmospheric and rain loss only exists in the first few km**

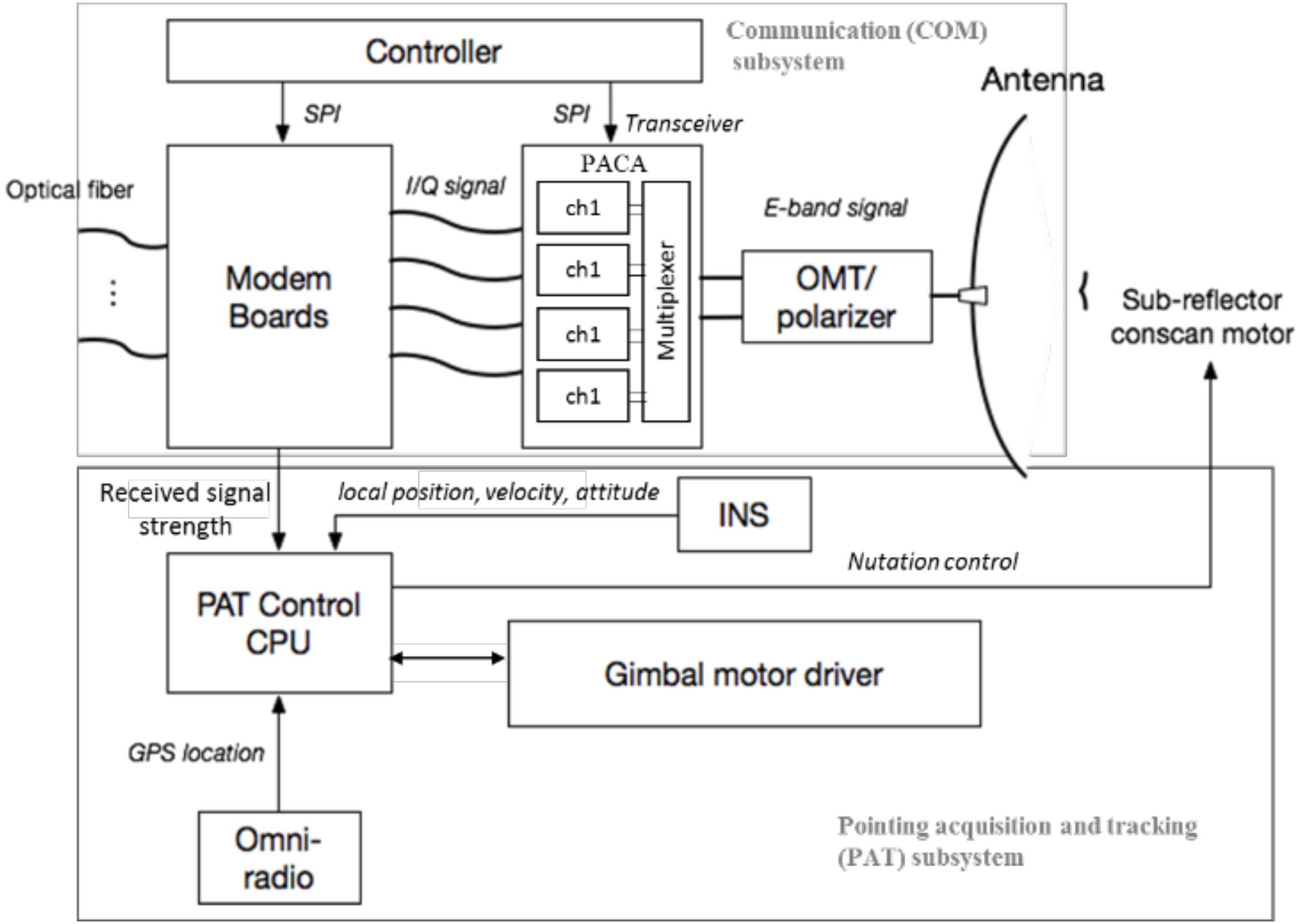
Total slant-path atmospheric attenuation (gas, clouds, rain, …)



Rain Loss (terrestrial)



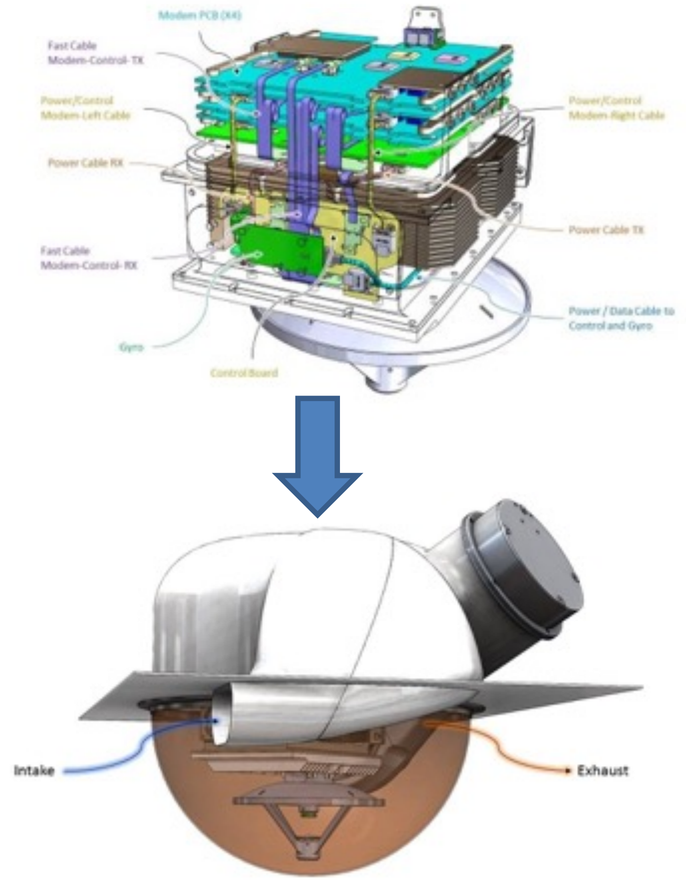
System Architecture Diagram



- **All COTS Components**
- **FB Unique Architecture**

Implementation

Conceptual Design for Aquila HAP



First Prototype Air and Ground for Cessna Flights

Communication System Details

Baseband

- 2GHz channel bandwidth
- Max. Baud rate 1.6 GSps, up to 128QAM and 10 Gbps
- Adaptative modulation scheme control

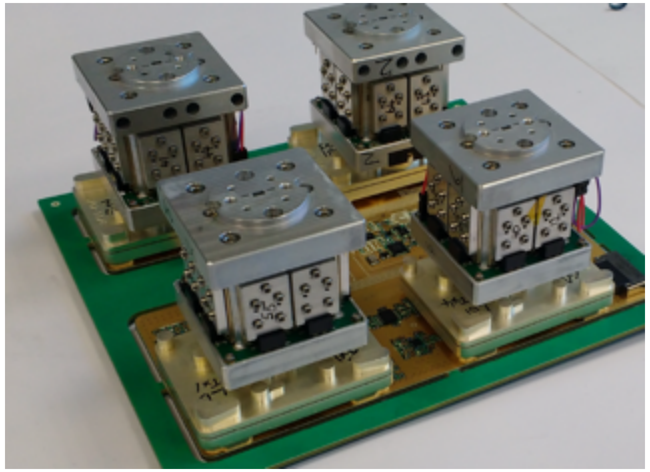
Transceiver

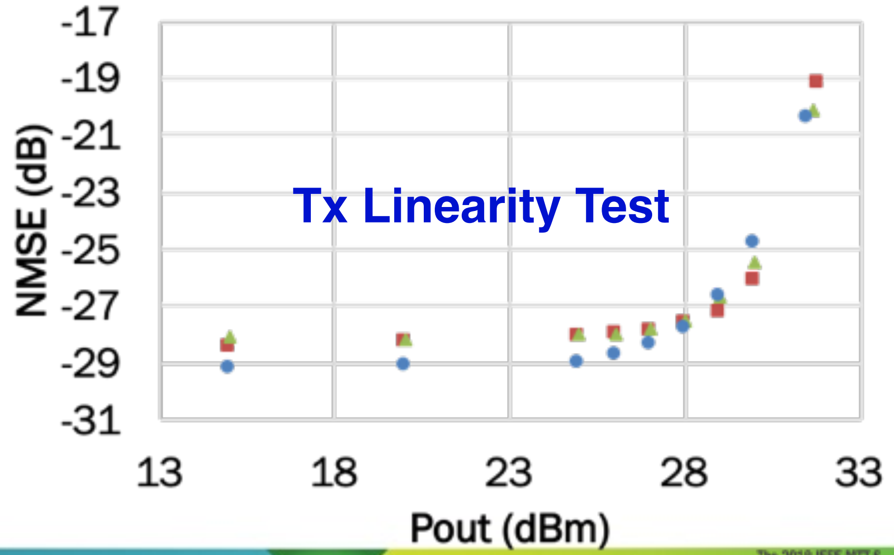
- Air-to-ground downlink: 71-73, 74-76 GHz
- Ground-to-air uplink: 81-83, 84-86 GHz
- Dual polarization: RHCP and LHCP
- Direct conversion architecture
- GaAs PA: P_{sat} = 34.5 dBm (Ground) and 32.5 dBm (Airborne)
- DC power consumption of each PA is 14W
- Weight of each PA is 0.16 kg with heatsink
- Rx noise figure 2.8 dB at LNA input

Known issues

- LO leakage cancellation
- Channel flatness and other signal impairments
- Tx linearity issue at high output power (>24dBm)
- PA efficiency is 6% at backoff for 64QAM signal

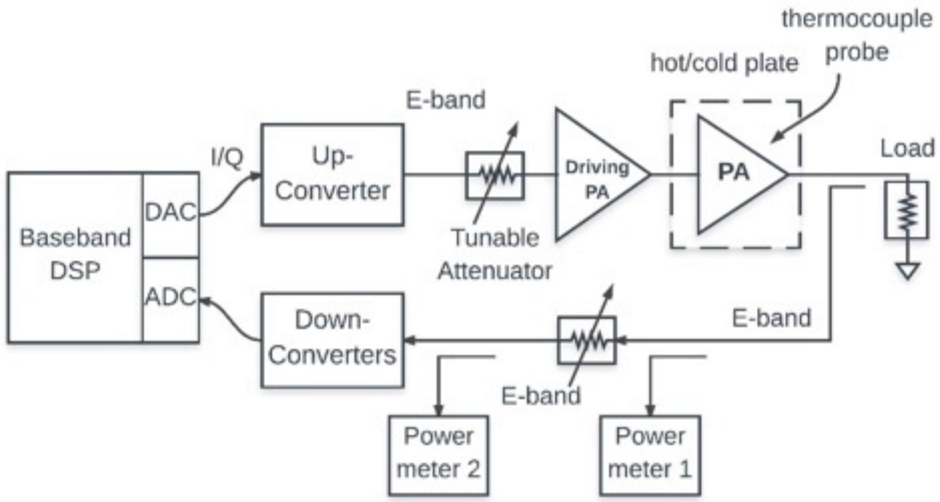
Airborne Transmitter Assembly





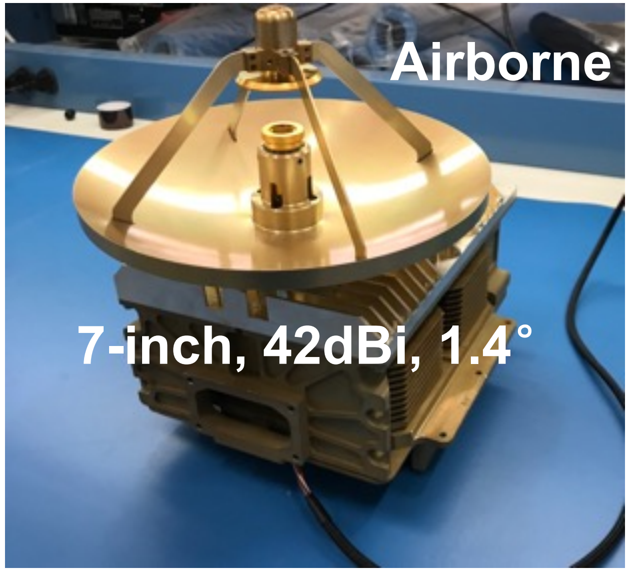
Digital Predistortion for E-Band PAs

- Memoryless 5th-odd-order digital predistorter: $y = a_1 x + a_3 x|x^2| + a_5 x|x^4|$
- Constraint optimization problem $\bar{a} = arg \min_{\bar{a} \in S}(EVM)\,, at\ P_{out} = P_0$

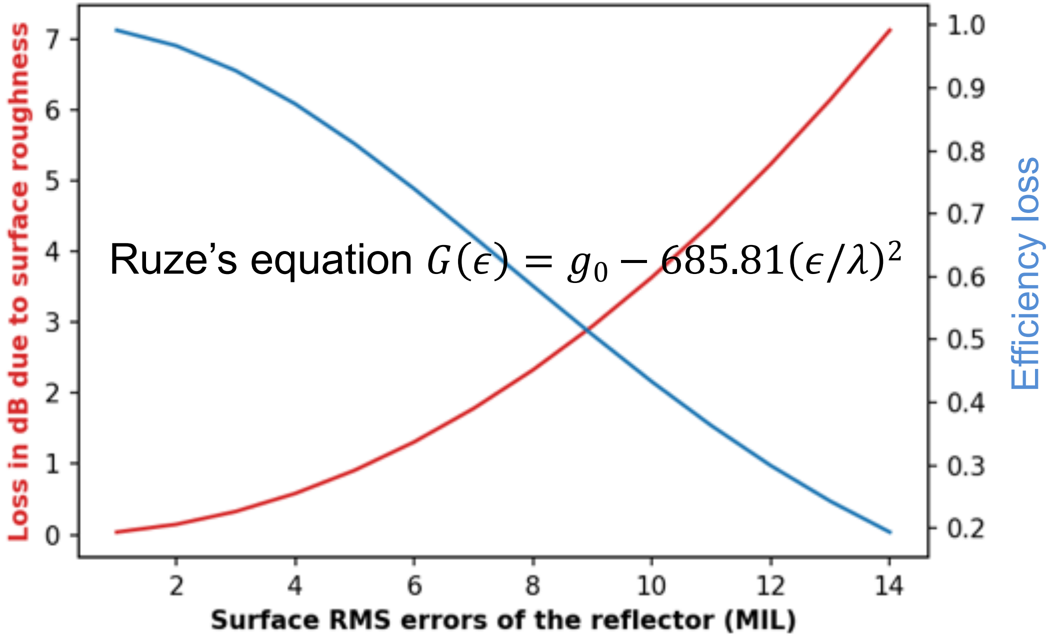


- **Automated test bench and optimization algorithm → DPD coefficients look-up table**
- **Improved the signal linearity by 4dB at the same output power for most COTS E-band PAs in general (no waveguide combining)**

Antennas

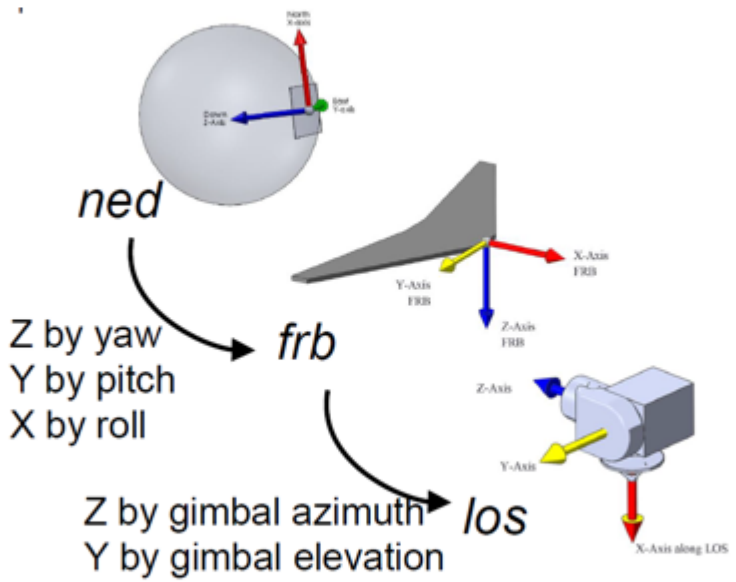


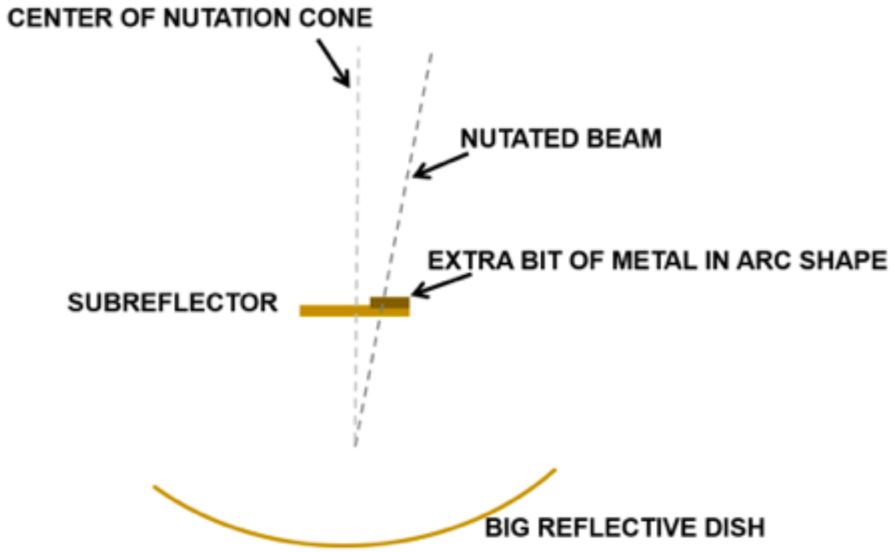
Efficiency loss due to surface roughness

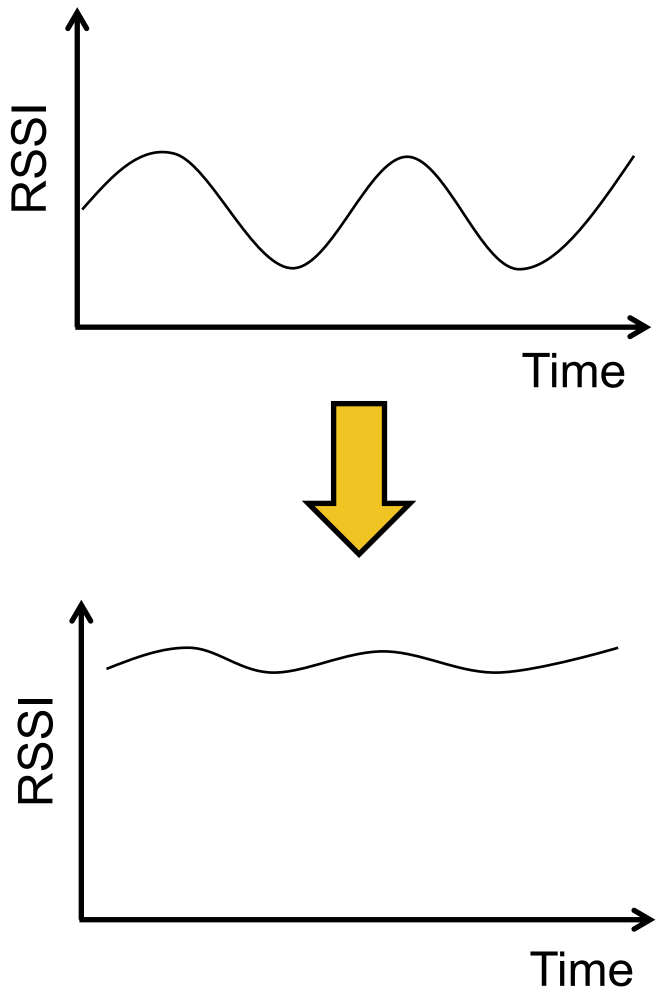


- **Trade-offs: Gain, pointing requirement, surface error ⇔ weight, wind load, cost**

Gimbal and PAT Control







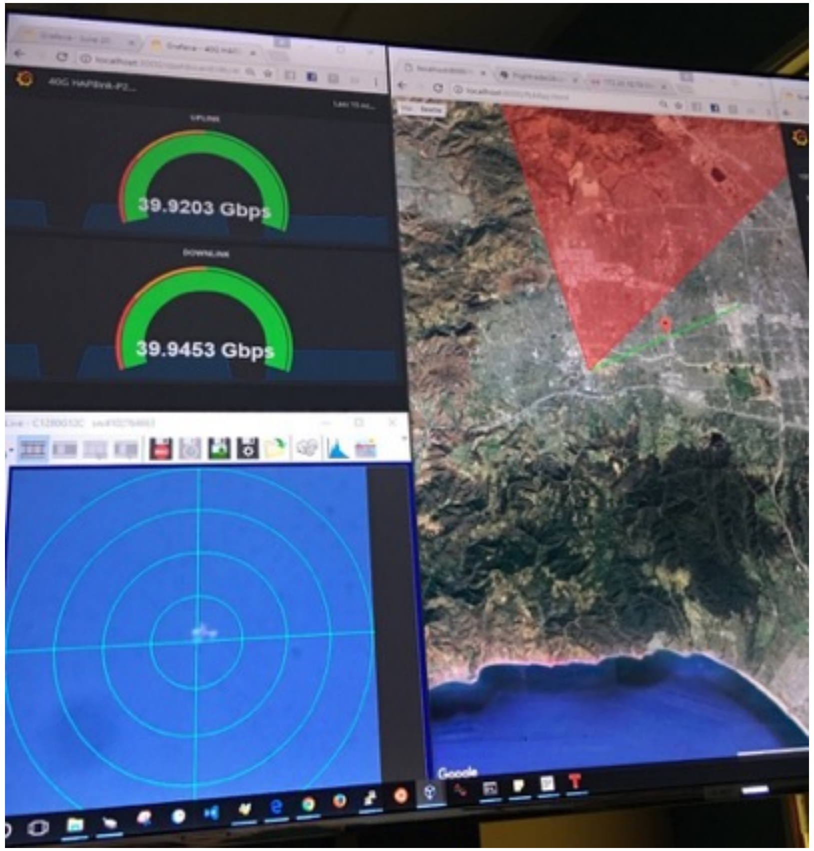
Ground antenna 0.2 degrees half-angle is 32dB of loss

- **Open-loop pointing: Real-time GPS information**
- **Closed-loop pointing: Conical scanning (Conscan)**

Flight Test

- **Cessna 210, 22 kft (6.7 km) altitude, 463 km/h speed, 8-12 km slant range**

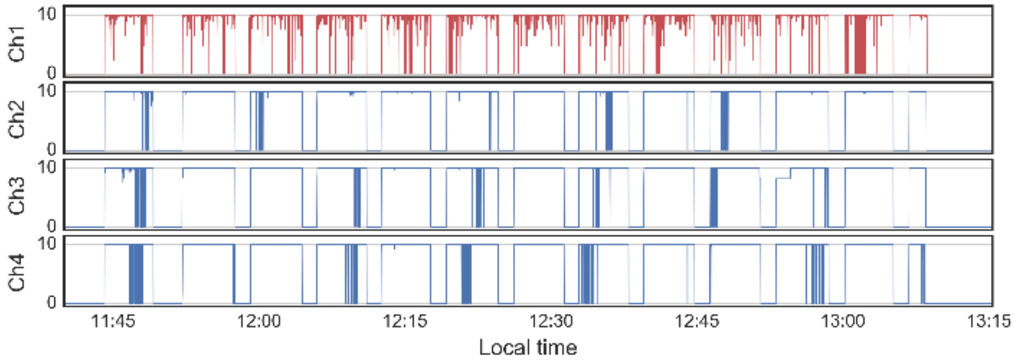
Demonstration



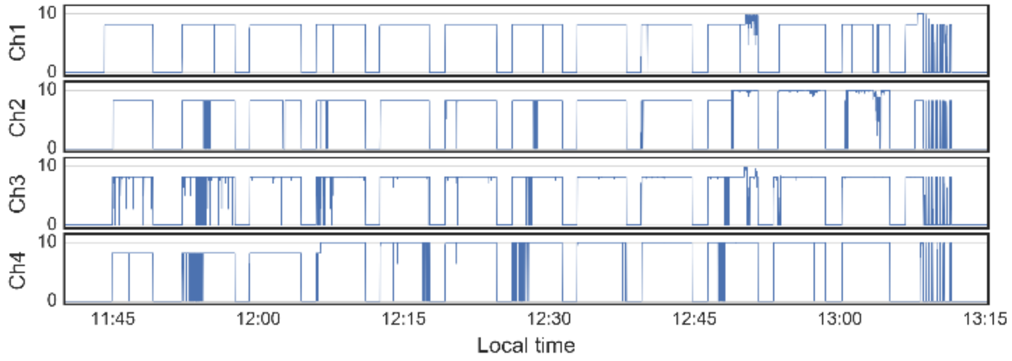
- Peak 40 Gbps bidirectional / Sustained 40 Gbps down and 36 Gbps uplink
- World record commercial high-throughput long-range air-to-ground link

Maximum Throughput

Air-to-ground downlink

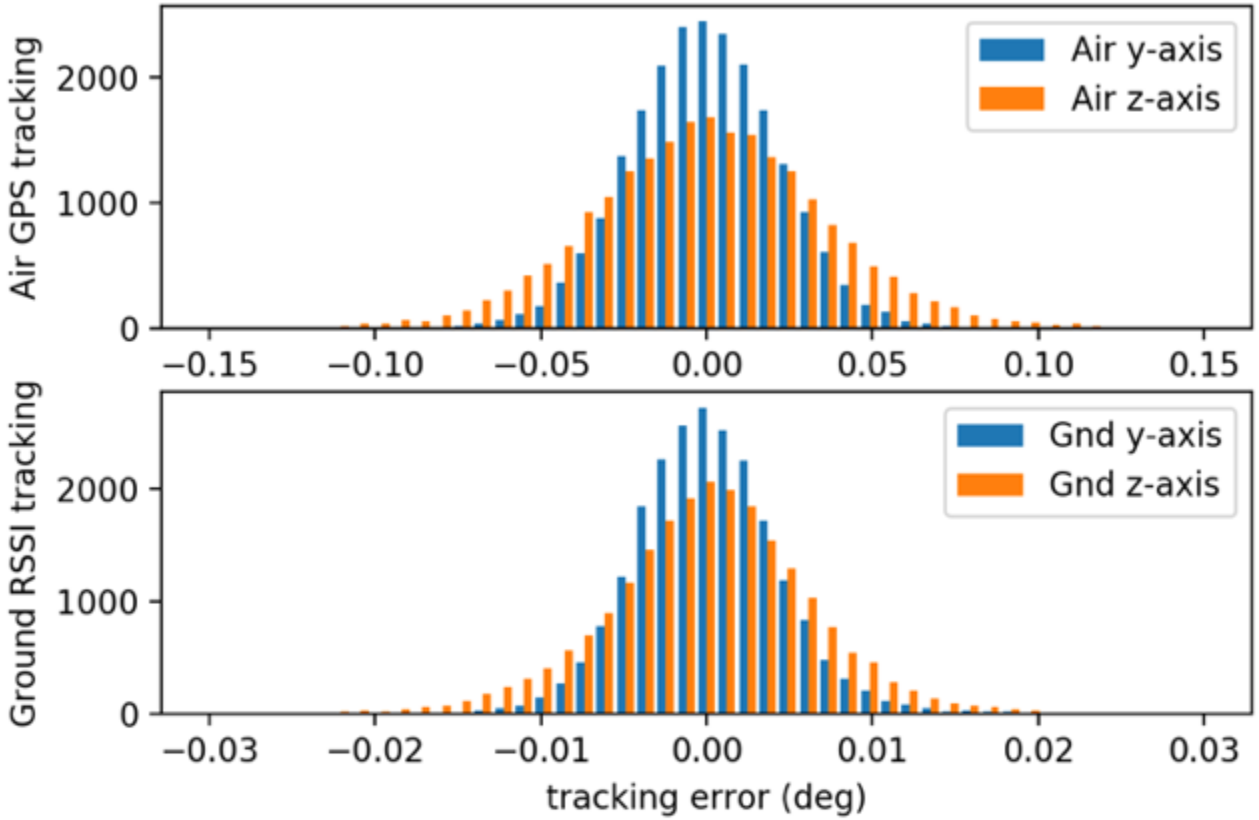


Ground-to-air Uplink



- **Manually configured at a fixed MCS level instead of using adaptive modulation control to characterize maximum throughput and link performance**
- **Wiggling mainly due to the suboptimal axial ratio on the ground side and suboptimal ground transmitter linearity (all solvable)**

Measured Pointing Accuracy



Pointing accuracy: <0.1° for air side and <0.02° for ground terminal

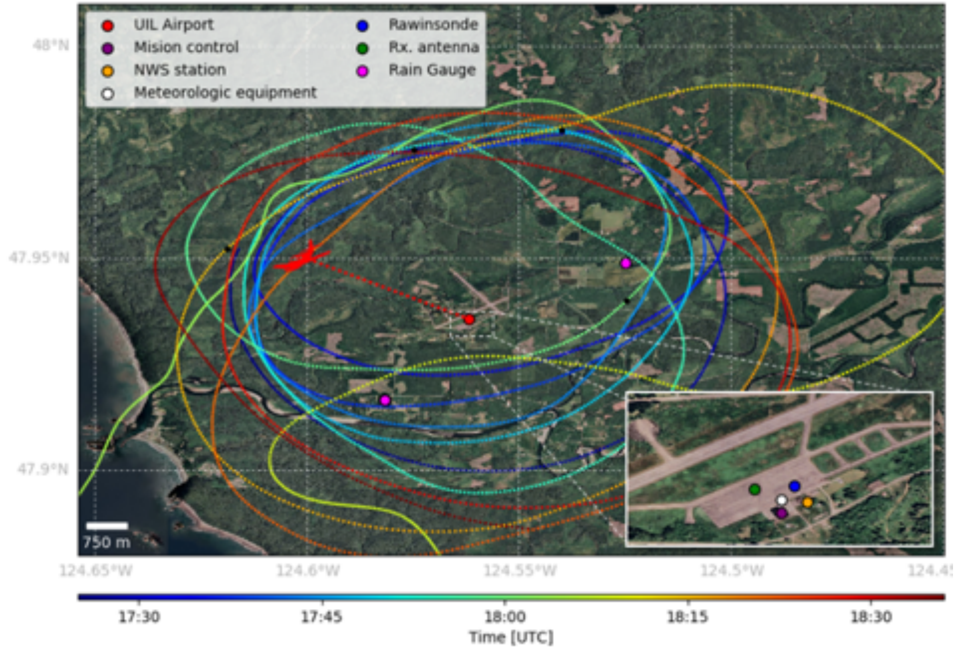
ITU Rain Model Validation

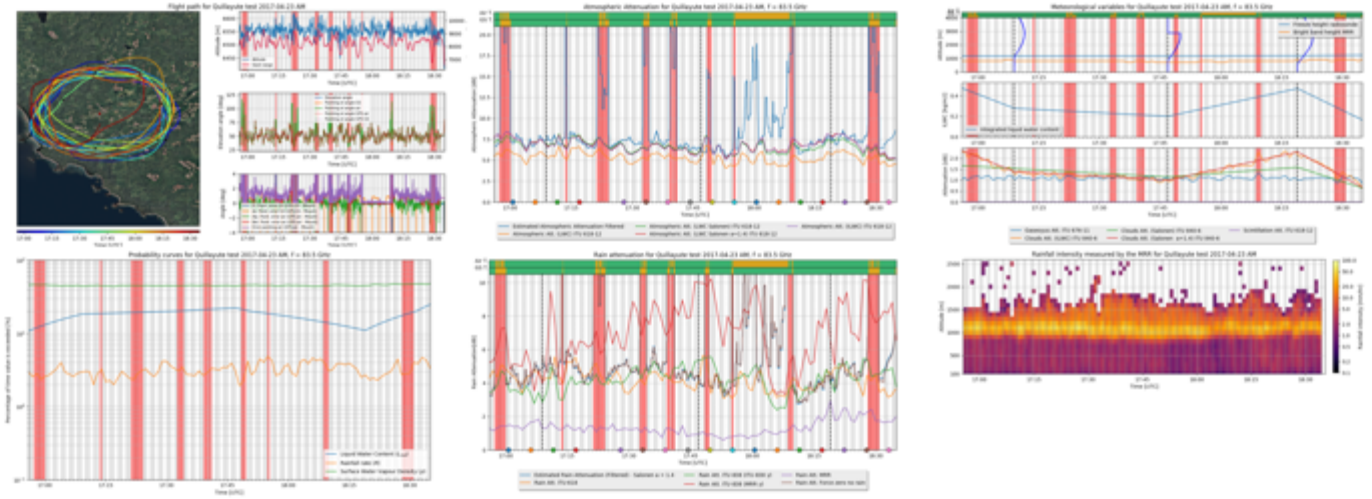
- **ITU long-term rain and cloud attenuation statistics only recommended up to 55GHz**
  - Gaseous (Rec. ITU-R P.676), clouds (Rec. ITU-R P.840), scintillation (Rec. ITU-R P.618), and rain (**Rec. ITU-R P.618**) contributions to the total atmospheric attenuation
- **Two week flight campaign in Quillayute, WA for a quick verification up to E-band**

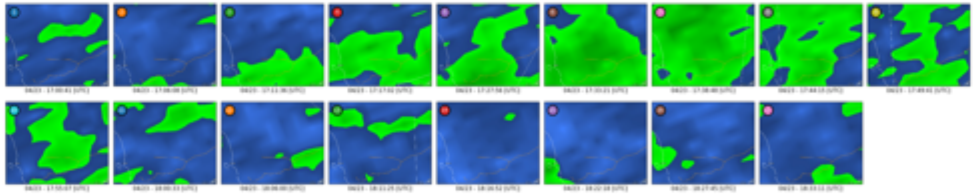
Quillayute, WA is the rainiest place in the Continental US

Measurement Setup and Post-Processing

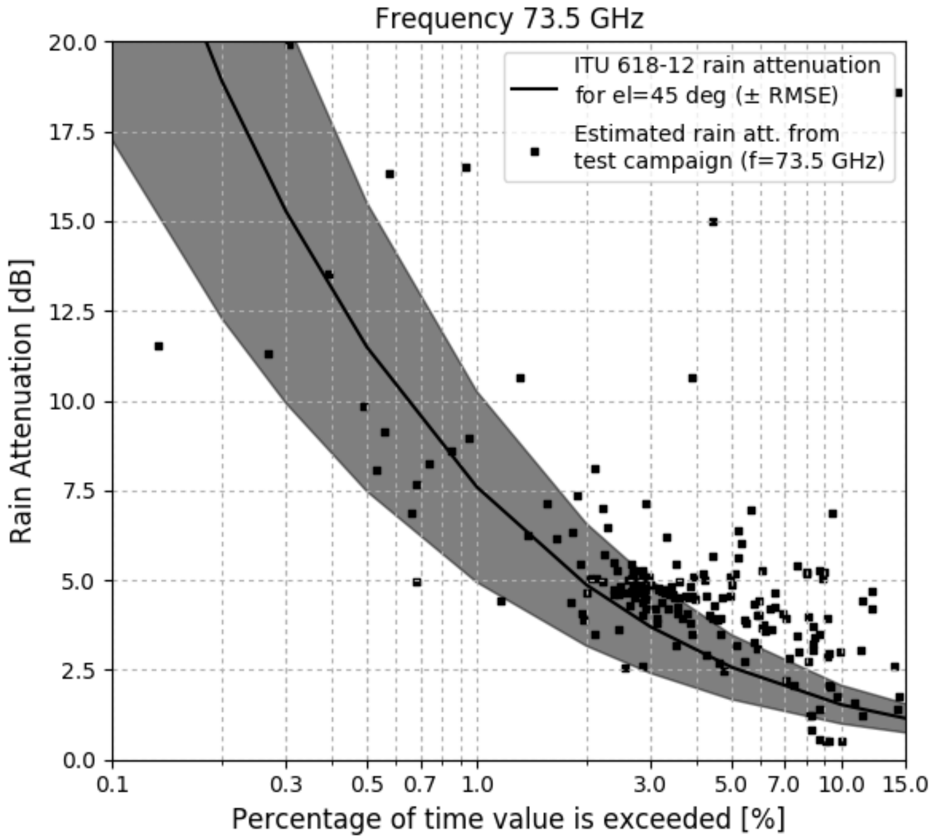
- Equipment: 24GHz Micro Rain Radar (MRR), radiosondes, meteorological ground station, drop size disdrometer, and E-band air-to-ground system

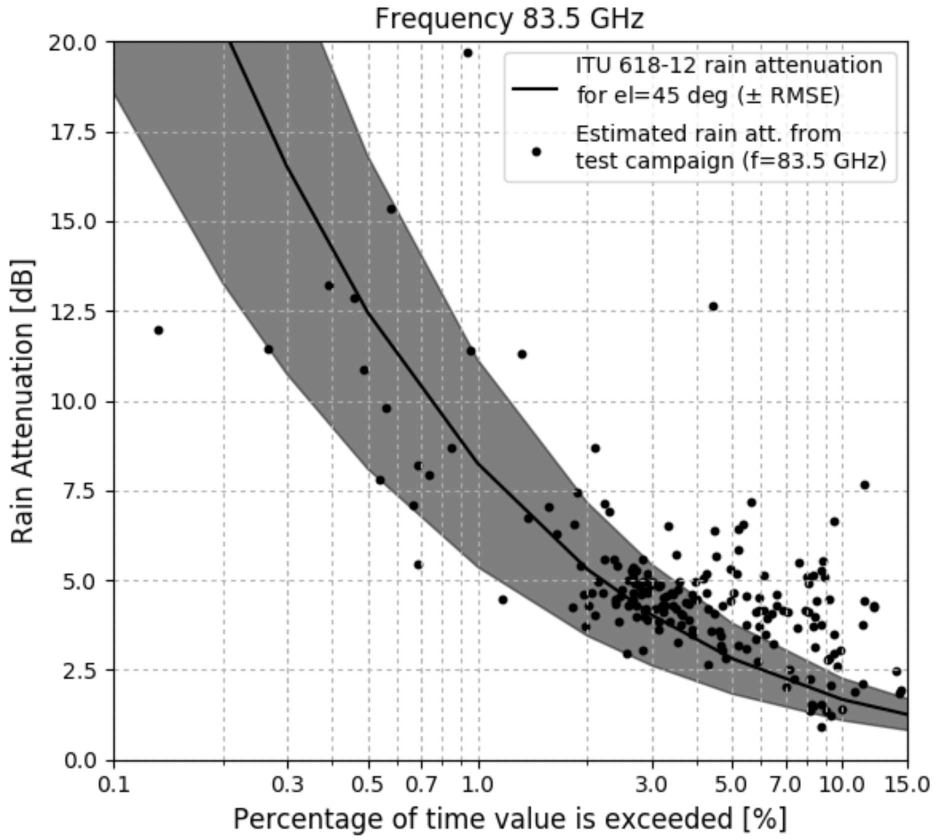






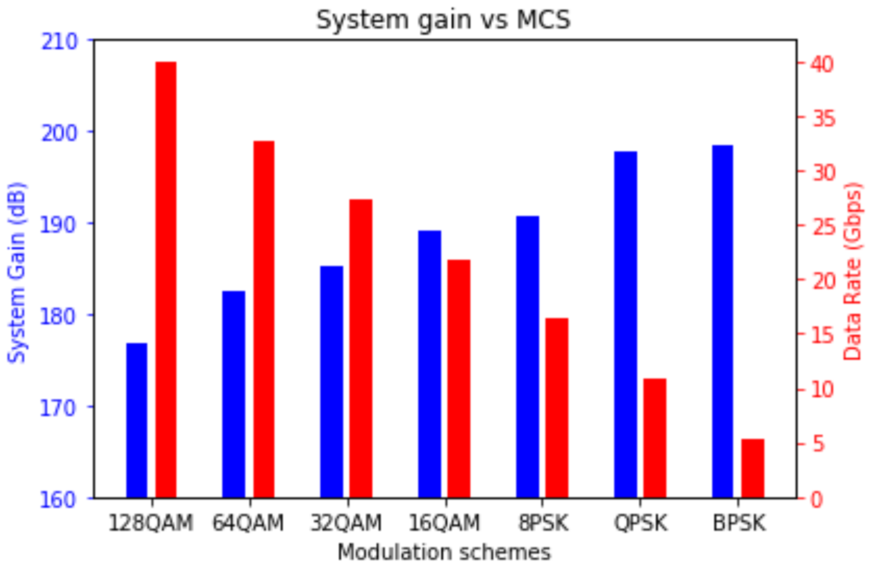
E-Band Rain Loss Measurement Campaign

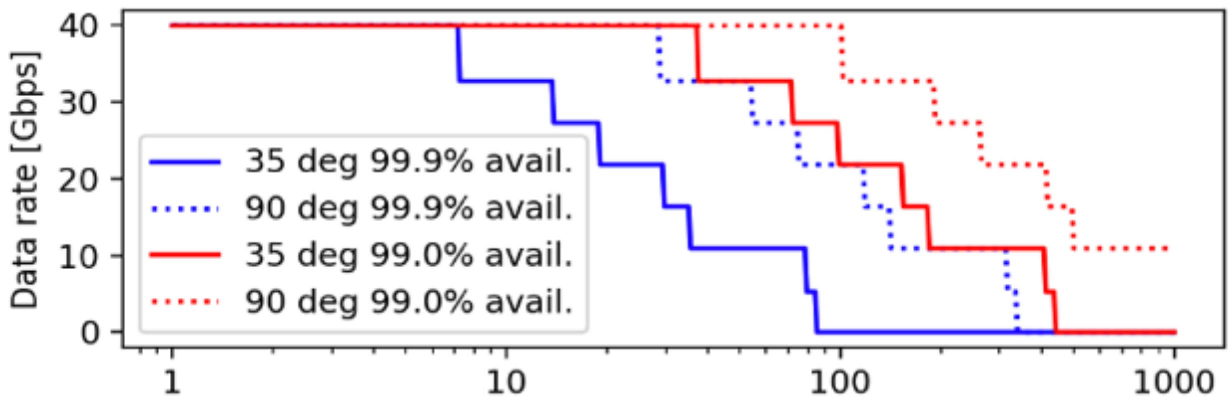




- **No strong evidence to suggest that the ITU-R P.618-12 recommendation to estimate rain attenuation in E-band is not valid**
- **Long-term statistical atmospheric loss data needs to be further collected**

System Gain and Link Availability

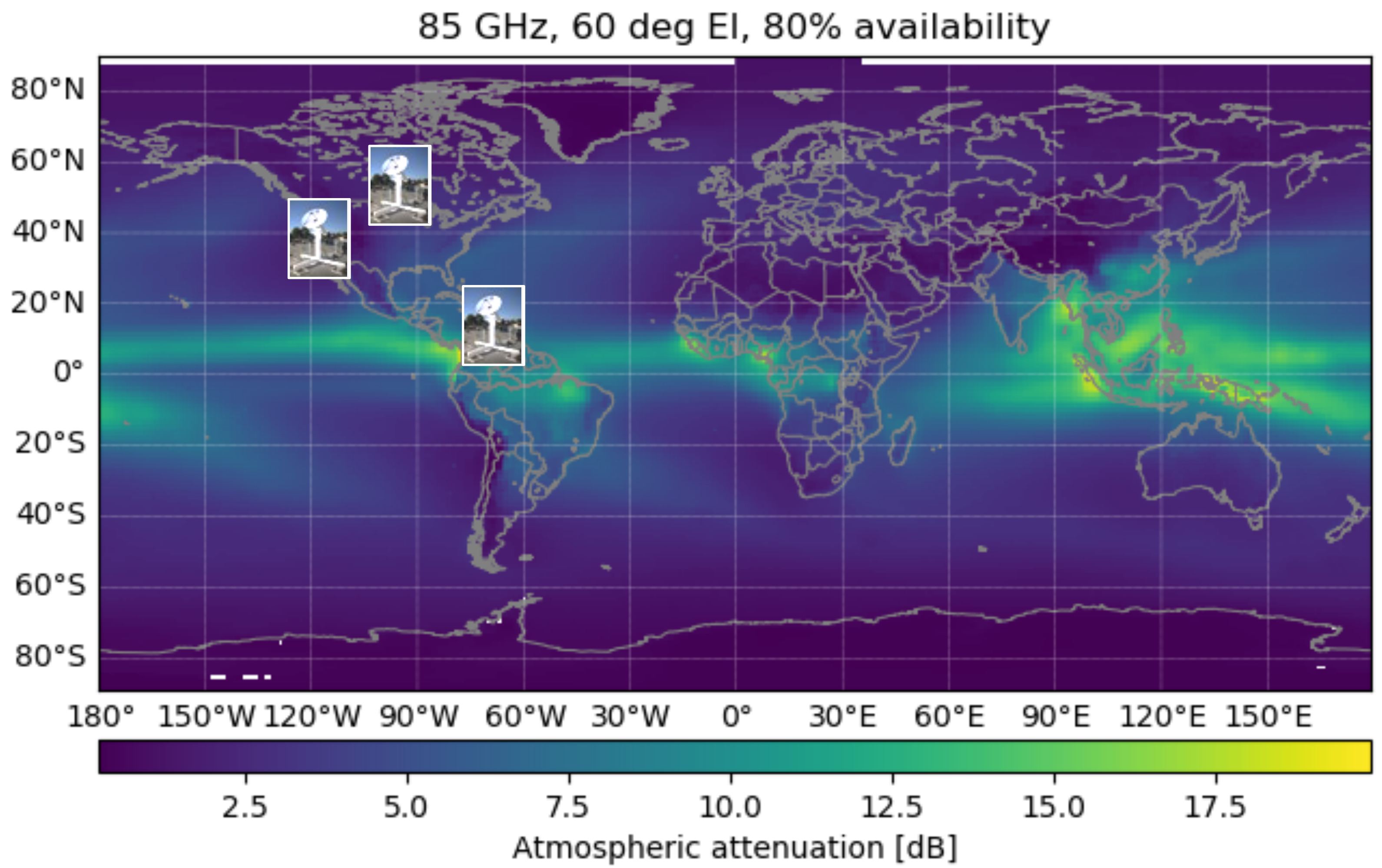




Based on the measured system performance and ITU model verification:

- **40 Gbps link can be sustained up to an altitude of 28km for a 99.9% availability in Los Angeles region at 90° elevation angle (zenith)**
- **10 Gbps link can be maintained for altitudes up to 310km**
- Note the impact of rain on the XPD degradation is not considered

LEO Constellation w/ Multiple Ground Terminals



Assume uncorrelated rain events with large separation of ground terminals (>1000km)

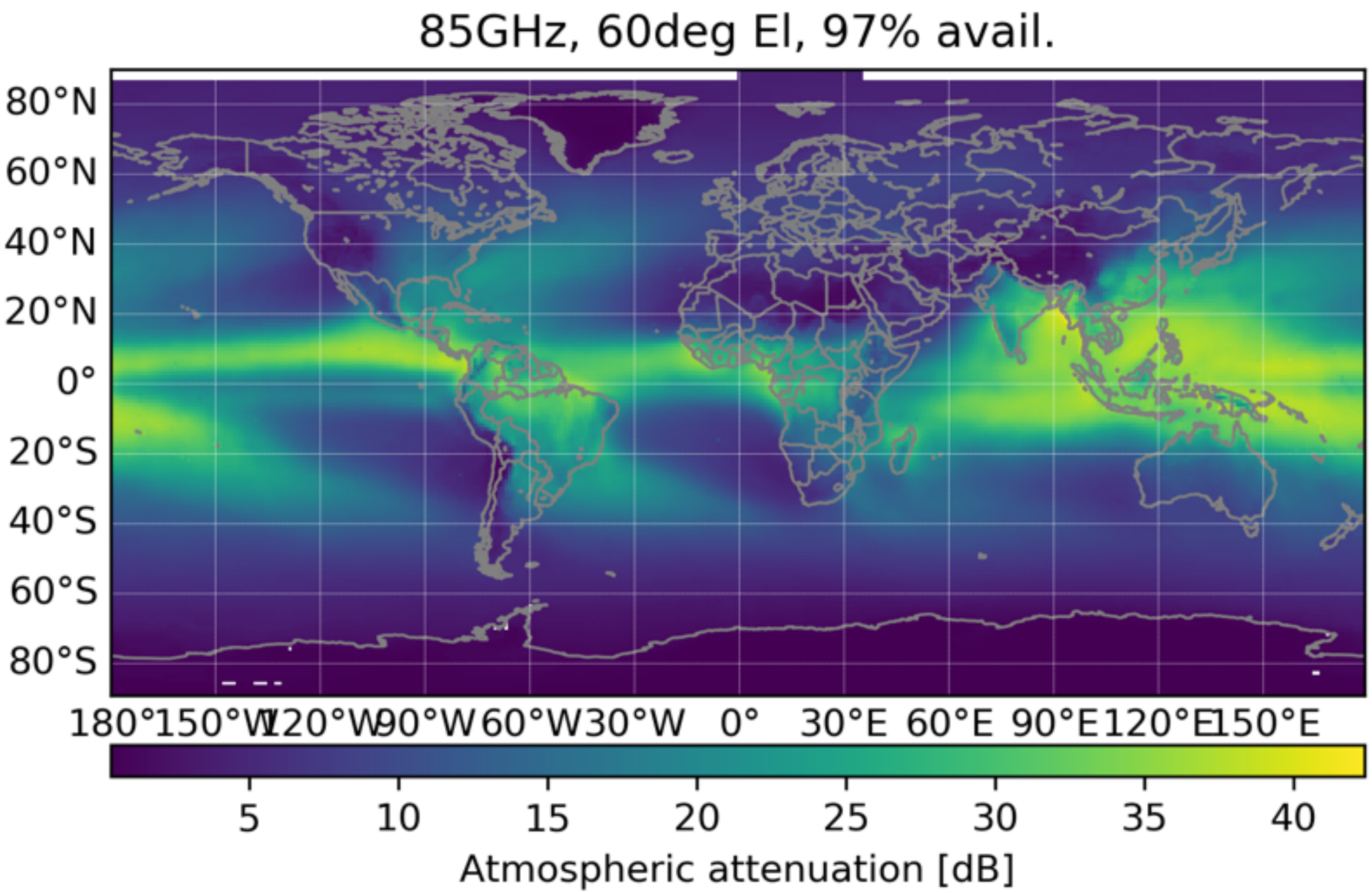
$$p_n = 1 - (1 - p)^n$$

Link Availability p_n(%) w/ Multiple Ground Terminals		
Single	Double	Triple
80	96	99.2
90	99	99.9
97	99.91	99.9973
98	99.96	99.9992
99	99.99	99.9999

Summary

- First commercial E-band prototype with sustainable 40/36Gbps down/uplink air-to-ground communication link
- Airborne terminal consumes 247 Watts power and weighs 11.8 kg
- Pointing accuracy <0.1° for airborne terminal, <0.02° for ground terminal
- Quillayute rain test did not find any strong evidence the ITU-R P.618-12 recommendation to estimate rain attenuation in E-band is not valid
- For HAP application, 40 Gbps link can be sustainable up to an altitude of 28km for a 99.9% availability in Los Angeles and similar regions
- For LEO constellation application, E-band high-throughput link can cover most parts of the world with 80% single terminal link availability and much higher link availability (e.g. 99.99%) with multiple terminals

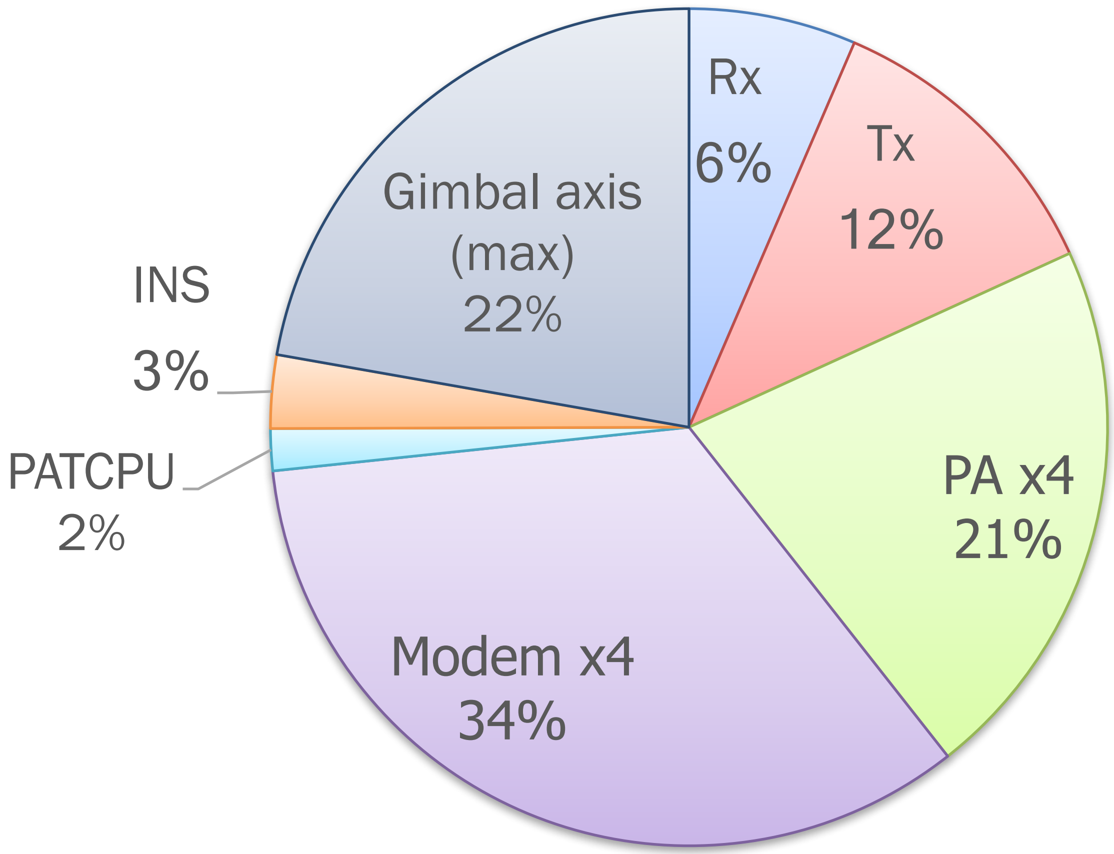
Global Total Atmospheric Attenuation Modeling



Simple Link Budget Sheet for 64QAM 32Gbps throughput at BER=10^{-9}

	HAP	LEO satellite
Slant range	50km	1000km
FSPL@85GHz	165	191
Aggr. Ant. Gain	100	100/106
Rx sensitivity	-56	-56
PA power	29	29/40
Margin for Atm. Att. (dB)	20	-6/11

Appendix: Power consumption in the Airborne terminal



Total power consumption 247 W