Design, Testing, and Operation of a Beacon Laser for a Portable Satellite Laser Communication Ground Terminal

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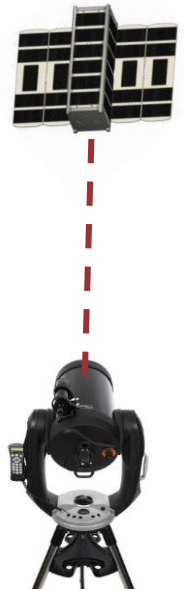
Presentation Overview

1. CLICK Mission and Optical Ground Station (PorTel)
2. Beacon Laser Design + Implementation
   - Electronics
   - Software
3. Testing & Safety
   - Electrical
   - Optical
4. Lessons Learned



CLICK Mission

- **CubeSat Laser Infrared CrosslinK (CLICK)**
  - Demonstration of optical communication
  - 3U CubeSats
- **Portable Telescope for Lasercom (PorTel)**
  - Custom Optical Ground Station
  - Built with 28 cm commercial telescope

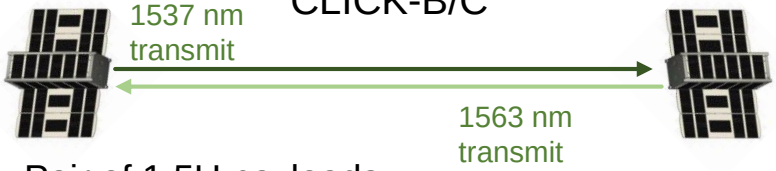
→ See CDW '23 talk by Peter Grenfell "On-Orbit Operations and Lasercom Experiment Results for the CLICK-A Mission"

→ See thesis by Jacob Harburg "On-Orbit Operations and Lasercom Experiment Results for the CLICK-A Mission"

CLICK-A

- Single 1.2U payload
  - Downlink capability
- Mission objectives
  - Validate fine pointing system
  - Validate PorTeL ground station
  - ≥10 Mbps downlink

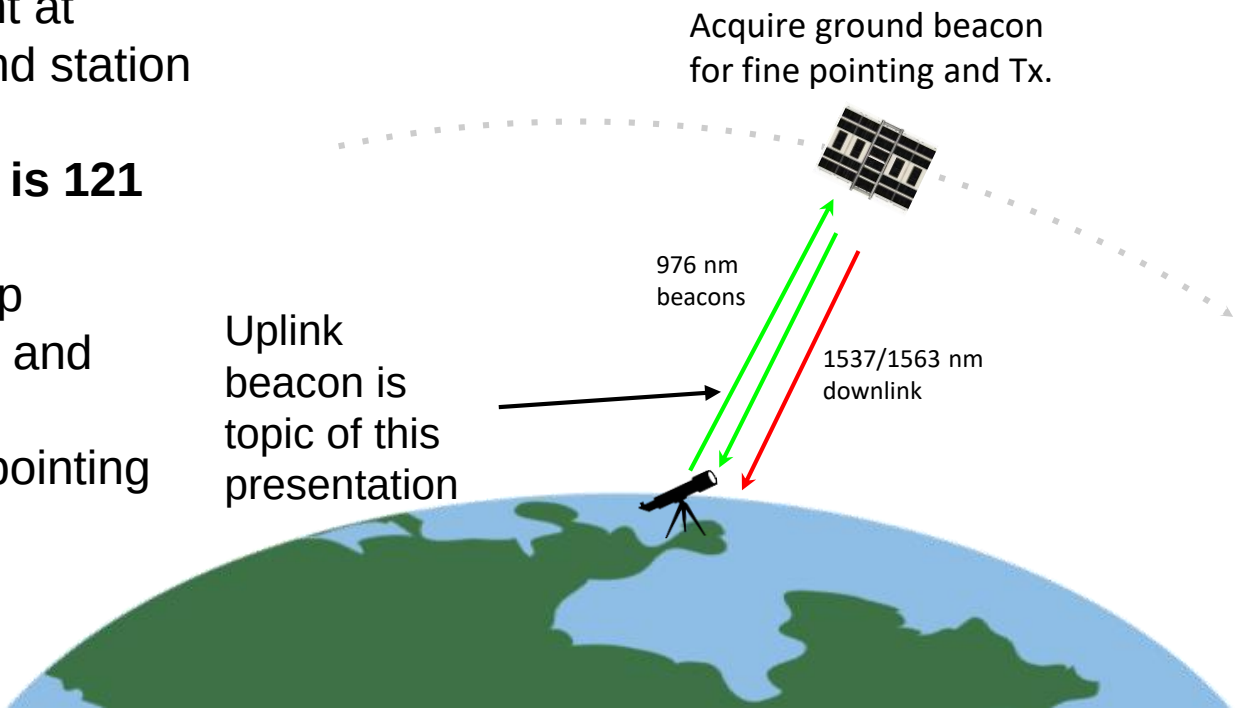
CLICK-B/C



- Pair of 1.5U payloads
  - Downlink and crosslink capability
- Mission objectives
  - ≥20 Mbps full-duplex crosslink
  - <0.5 m ranging
  - Demonstration over range 25 km – 580 km

CLICK Pointing (ground)

- Spacecraft needs to point at ground station and ground station at spacecraft
- **Data laser FWHM (B/C) is 121 µrad**
- Challenging for open loop pointing (bus uncertainty and TLEs become stale)
- Solution: Achieve initial pointing with beacon

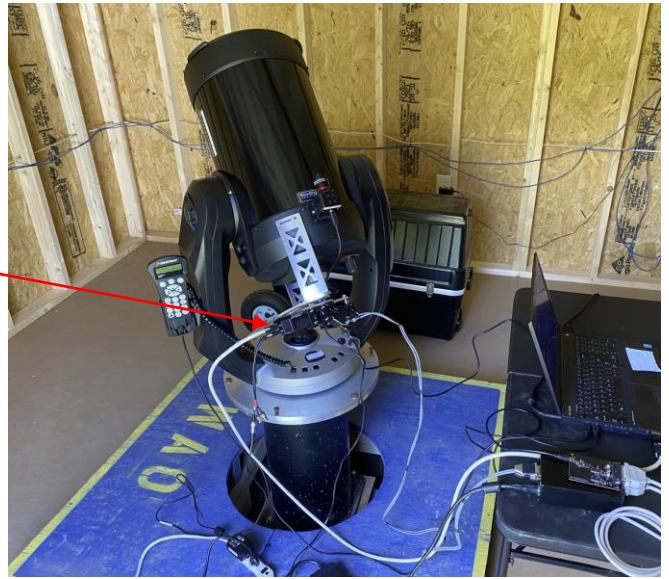


Beacon Requirements / Challenges

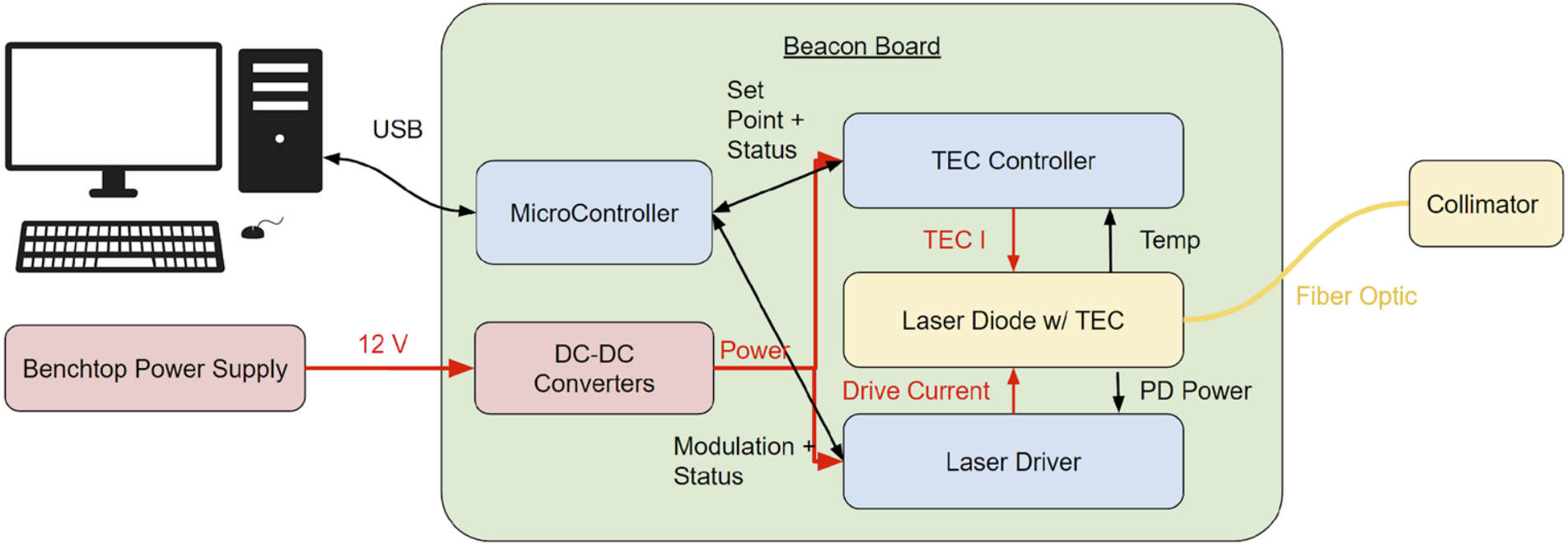
- 5 Watts peak optical power
  - 5000x safe level for invisible wavelength
- Form factor compatible with mounting on PorTel
  - ~100s grams
- Modulation with 3 kHz sine
- Temperature regulation for outside environment + laser temp stability

Together these requirements necessitate a custom implementation

PorTel Optical Ground Station



Beacon System Diagram

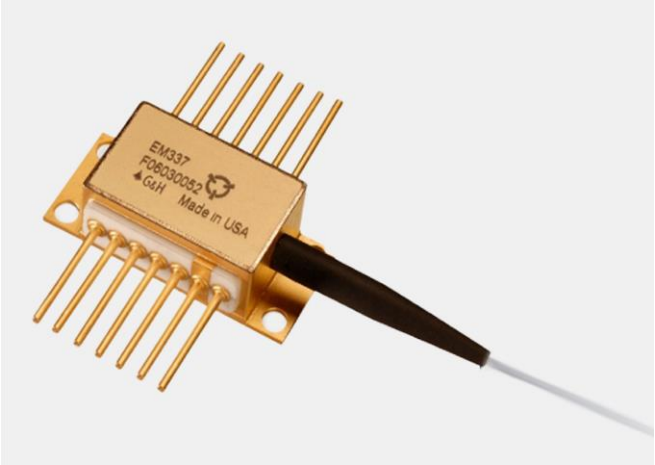


Major Component Selection

Laser Diode

Gooch & Housego EM336

- 5 W
- Multimode fiber coupled
- Integrated TEC



Collimator

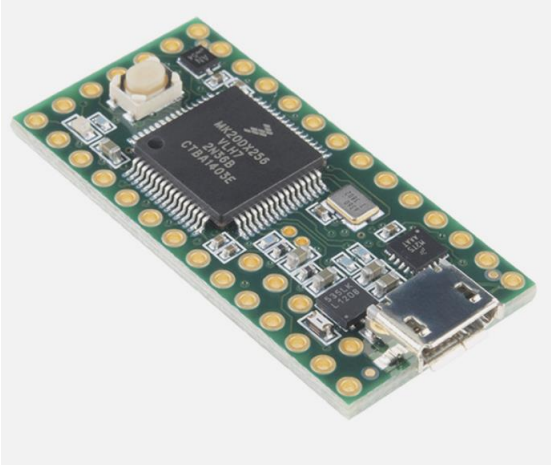
Thorlabs ZC618APC-B

- Adjustable focus
- APC Connector

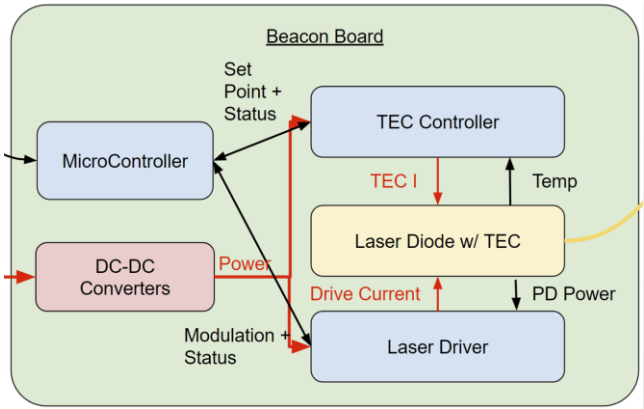
Microcontroller

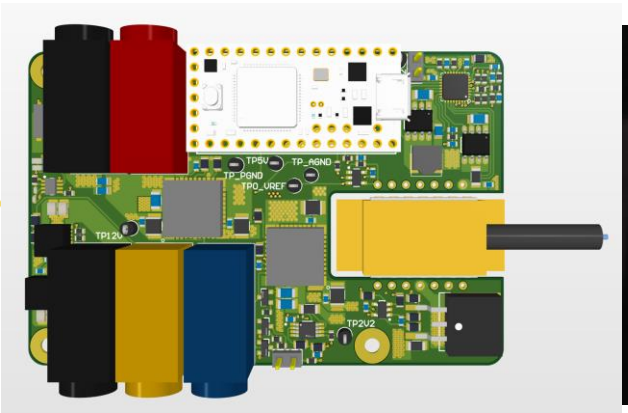
PJRC Teensy3.2

- Integrated DAC/ADC
- Small form-factor
- Arduino IDE supported



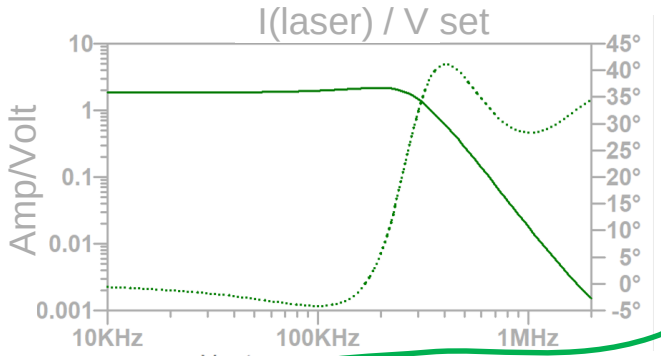
Electronics Implementation





https://github.com/MIT-STARLab/PorTeL-Beacon

Laser Driver



Optical Power Control Loop

Software PID

+2.2V

+3.3V

120 pF

100 Ω

V set

Current Control Loop

62 kΩ

3.3 kΩ

10 Ω

470 µF

10 kΩ

1 kΩ

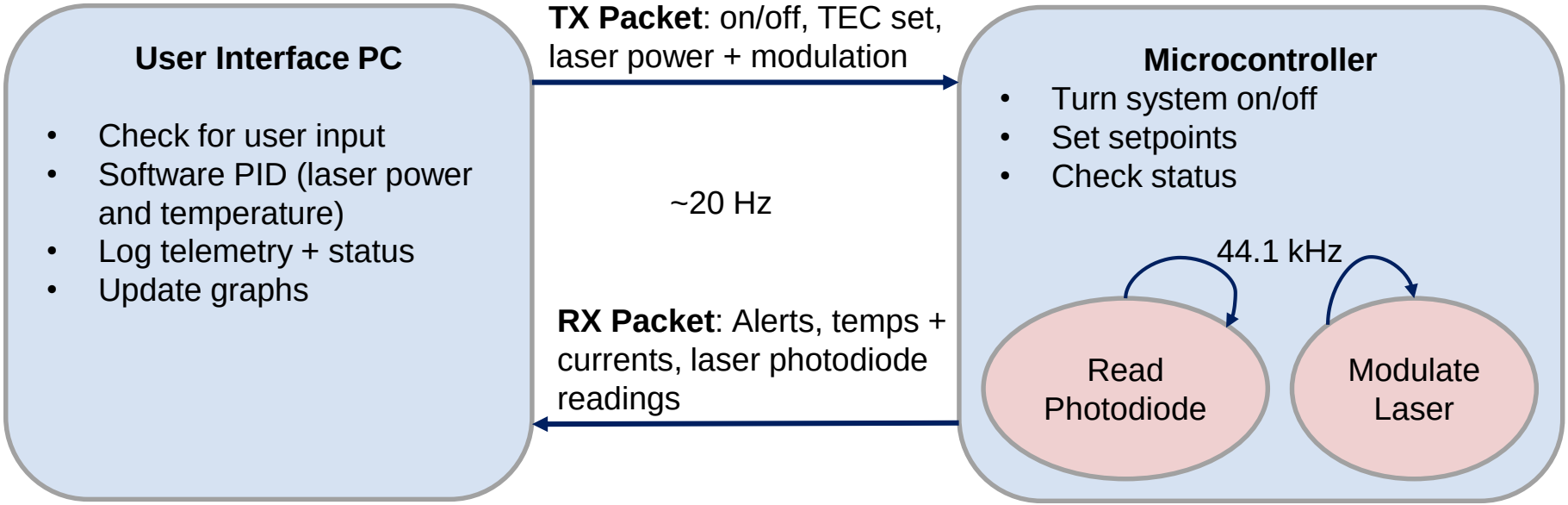
0.025 Ω

+3.3V

PD Sense

0.4 V/W sense

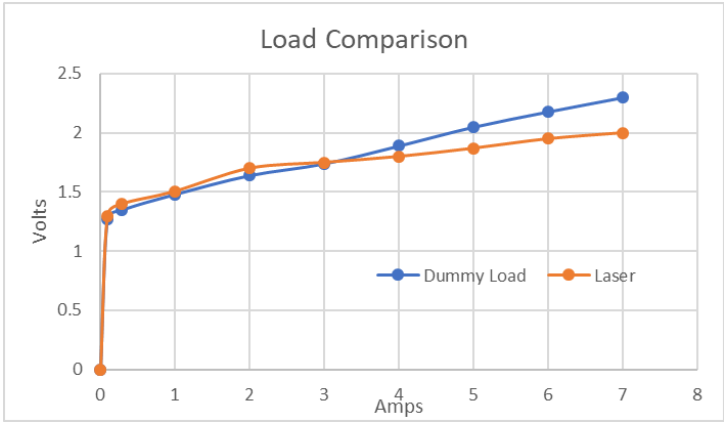
Software Implementation



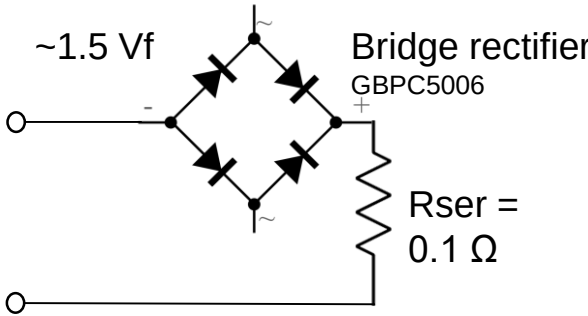
https://github.com/MIT-STARLab/PorTel-Beacon-sw

Electrical Testing

- Incrementally verify system
- Mitigate safety risks to laser diode and operators
- Start with PCB without laser installed, verify electronics
  1. Visual inspection
  2. Check power supply levels
  3. Verify safety interlock
  4. Verify communication loop with user interface
  5. Operate system with dummy load
  6. Install laser, repeat operations tests with fiber beam dump
  7. Connect to collimator



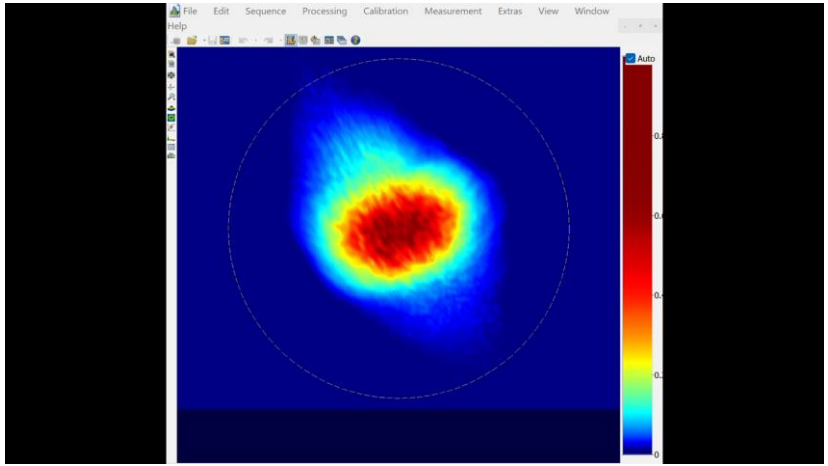
>20 W Dummy Load

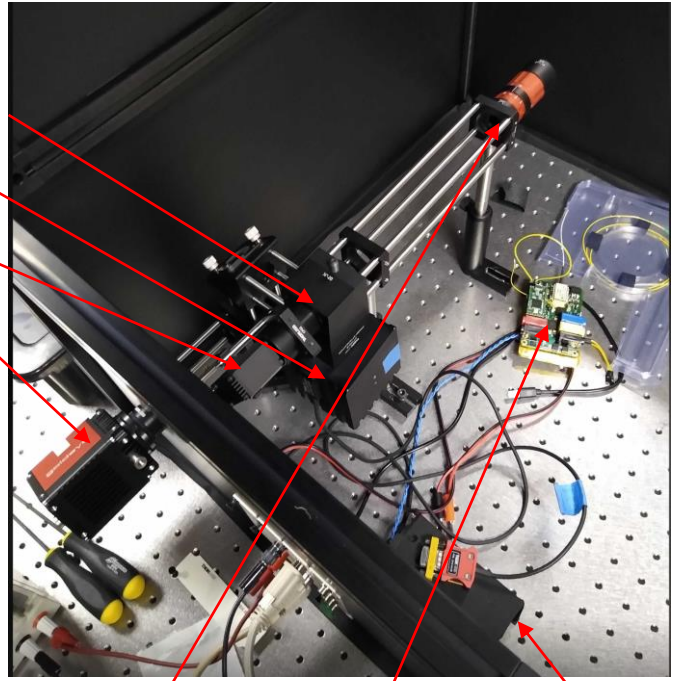


Optical Testing

- Measure optical power
- Adjust zoom collimator to 5.5 mrad FWHM
- Check profile

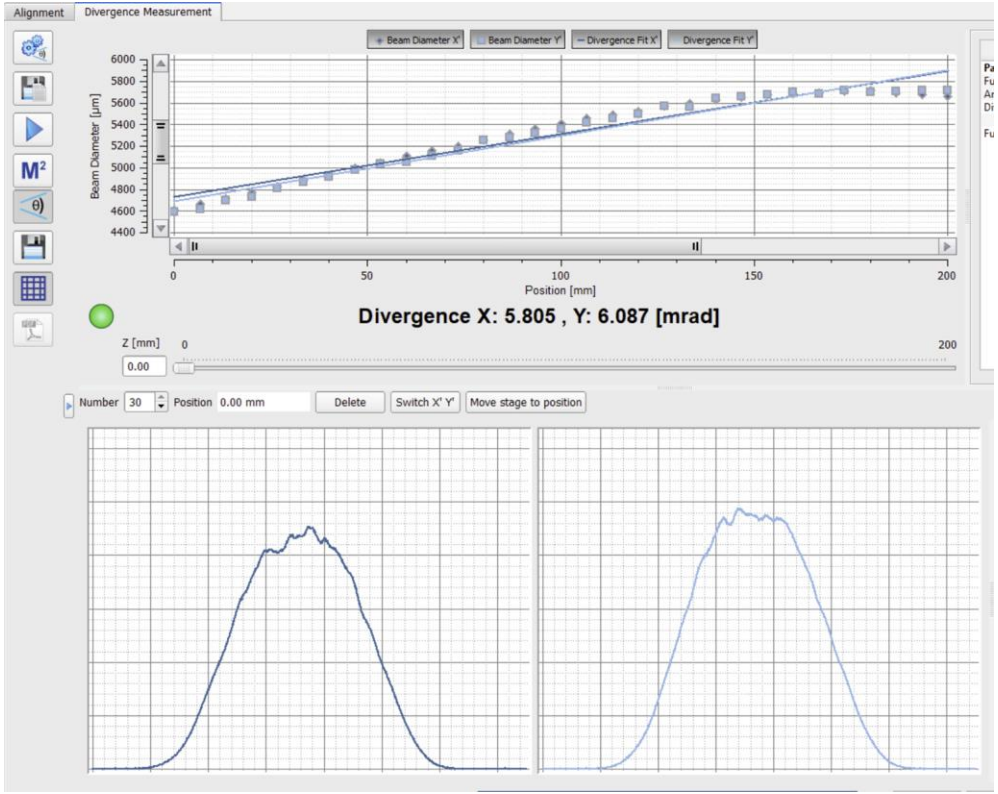
Multi-Mode Beam Profile





Beam Characteristics

Screenshot from Thorlabs Beam 7.0



Parameter	Value
Divergence	5.9 mrad
Total Optical Power	4.7 W
M^2	26
Waist Diameter	2.1 mm
Rayleigh Length	70 mm
Divergence Asymmetry	1%

Laser Safety

- 5 W, Class IV, Invisible Laser
- Safety plans made in coordination with MIT EHS

Testing

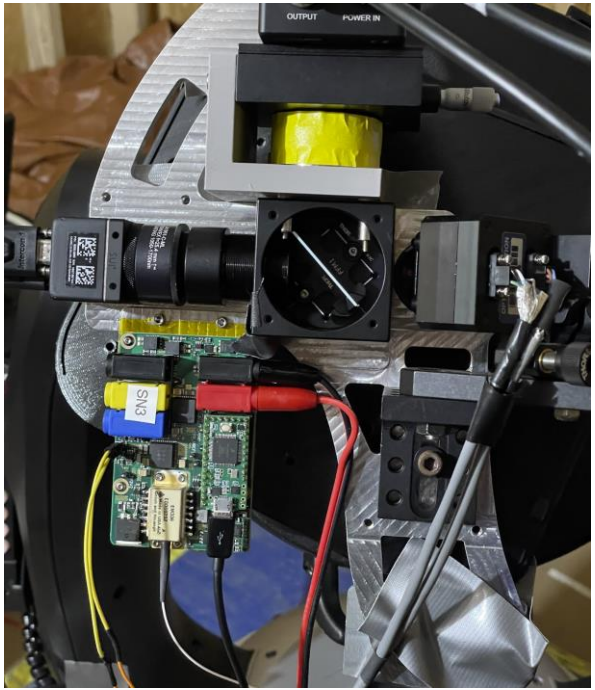
- OD 5+ Protective Eyewear
- Optical Box with door-interlock
- Fiber-coupled or cage-mounted optics
  - ~0.05% power into OD filter to free space and outside test equipment

Operation

- Keyed interlock prevents operation with people inside shed
- Minimum beam elevation 20° avoids public exposure
- Optical hazard distance for aircraft is 184 ft
  - FAA Evaluated and provided a “Letter of Non-Objection”

PorTel Integration

Beacon Board on PorTel Backend



Collimator mounted to front of PorTel

Optical Ground Station Shed

CLICK-A Operations

Operators with PorTel

Video of Tracking Satellite Laser from Ground

Lessons Learned

- It is difficult to independently check optical power output in the field
  - Need to be able to trust interface
- It is very difficult to measure divergence with long Rayleigh length
  - Long free space optics create safety hazards
- Expanding the beam into a large aperture would eliminate the need for some of the safety-imposed operation limits
- Operation software should include hooks for scripting

Conclusion

- Optical communication yields improved data rates for small SWaP form factors, but requires challenging pointing
- One method to achieve fine pointing is a large beamwidth beacon
- The CLICK beacon is a custom electronics system built around a commercially available laser diode component
- This beacon was used for the CLICK-A mission and will be used for CLICK-B/C

Questions?

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Software GitHub:
https://github.com/MIT-STARLab/PorTel-Beacon-sw/tree/api

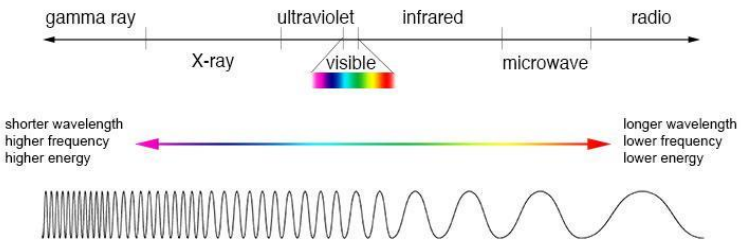
Hardware GitHub:
https://github.com/MIT-STARLab/PorTeL-Beacon

Backup

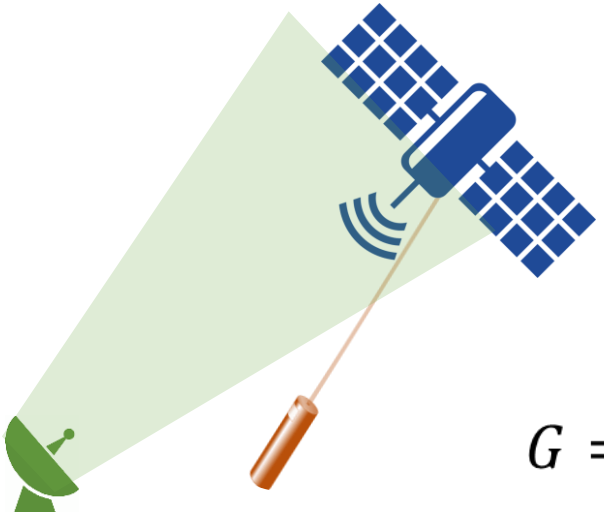
Laser Communication Pointing

$$capacity(\text{bps}) = B * \log2(1 + SNR)$$

Wider Bandwidth



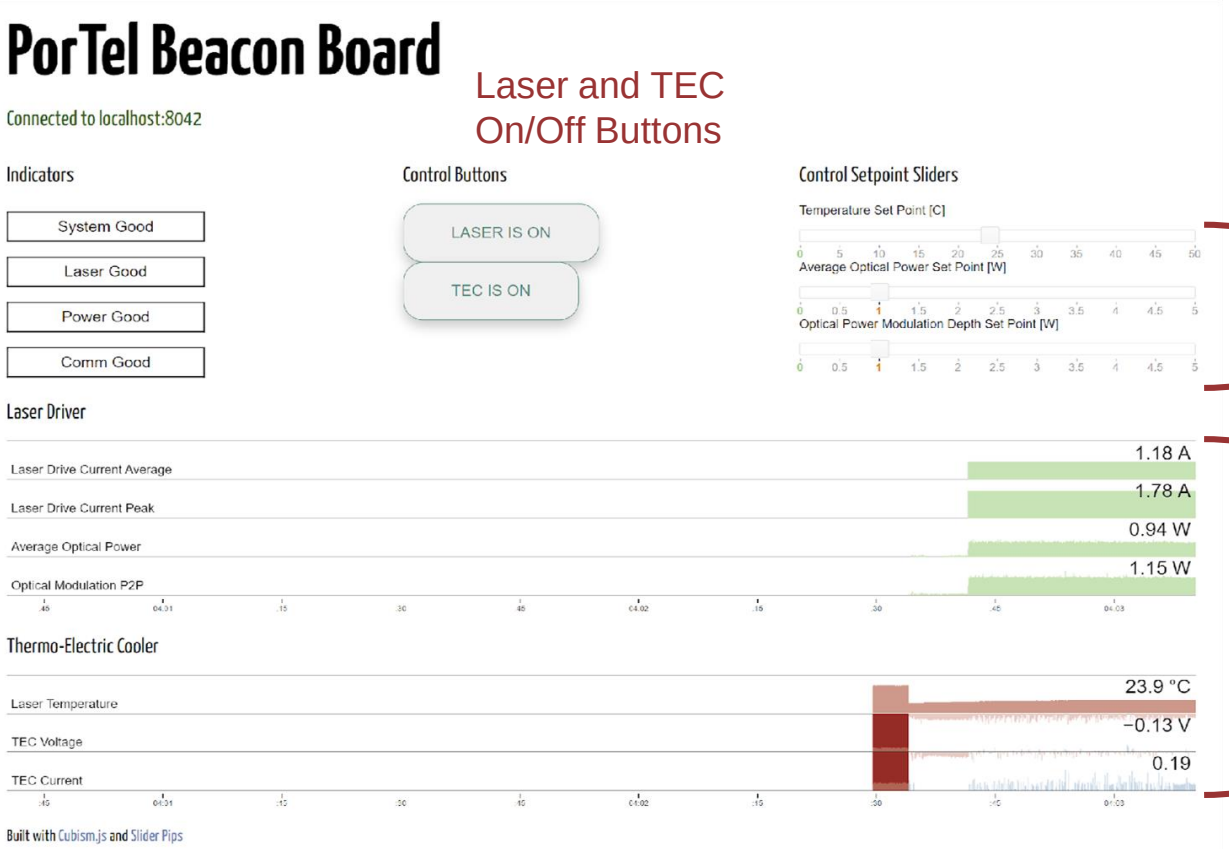
More Power to Receiver



$$G = \frac{4\pi A}{\lambda^2}$$

More gain + narrow beam + difficult pointing

User Interface



Indicator Lights
Red for error

User Defined
Setpoints

Status Graphs

PAT Staging & Budget

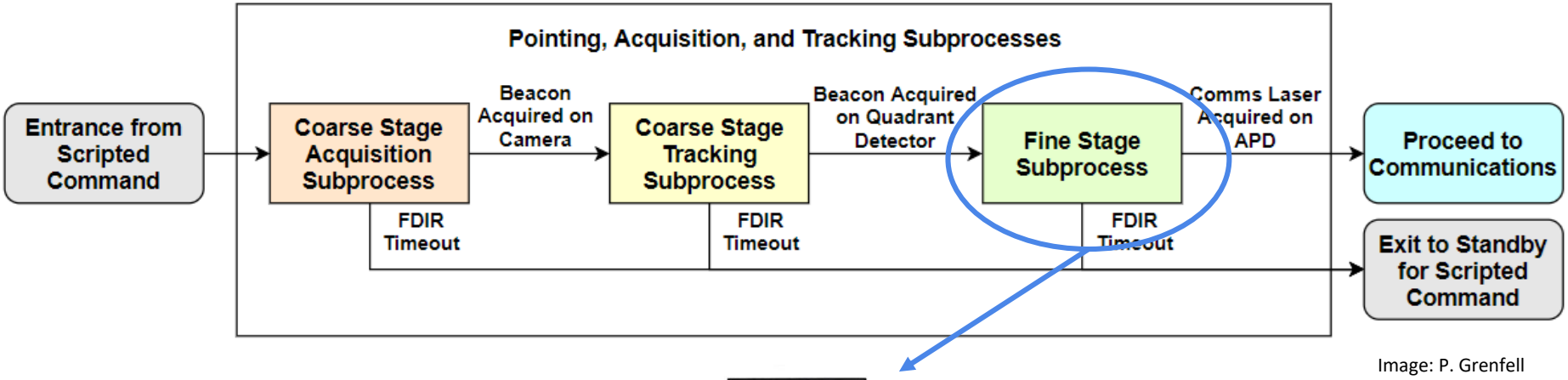
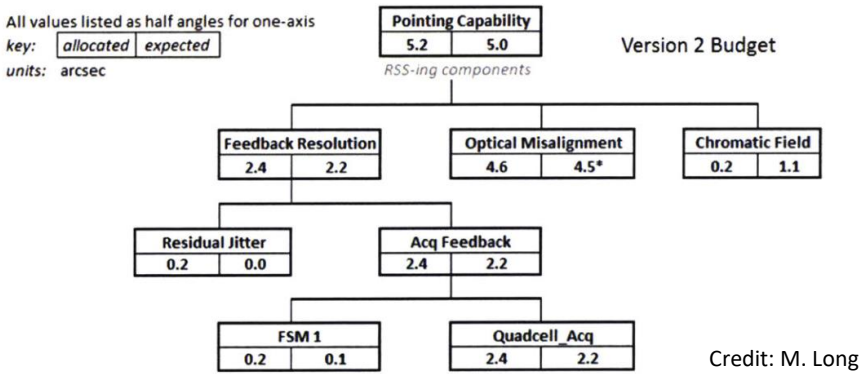


Image: P. Grenfell



Credit: M. Long

References

[1] Grenfell, Peter, et al. "Pointing, Acquisition, and Tracking for Small Satellite Laser Communications." Proceedings of the AIAA/USU Conference on Small Satellites, Advanced Concepts I, SSC18-WKI-01. 2018.

[2] Riesing, Kathleen Michelle. "Portable optical ground stations for satellite communication." PhD diss., Massachusetts Institute of Technology, 2018.

[3] Riesing, K. M., Yoon, H., & Cahoy, K. L. (2018). Rapid telescope pointing calibration: a quaternion-based solution using low-cost hardware. Journal of Astronomical Telescopes, Instruments, and Systems, 4(3), 034002.

[4] Čierny, Ondrej, and Kerri L. Cahoy. "On-orbit beam pointing calibration for nanosatellite laser communications." Optical Engineering 58.4 (2018): 041605.

Optical Ground Terminal

- MIT-developed Portable Telescope for Lasercom (PorTeL)
- Based on ⌀28 cm Celestron CPC1100
- Fitted with a custom backend & star camera
- Rapid setup and pointing calibration based on star camera quaternion solution (<15 min)

Credit: K. Riesing [2,3]

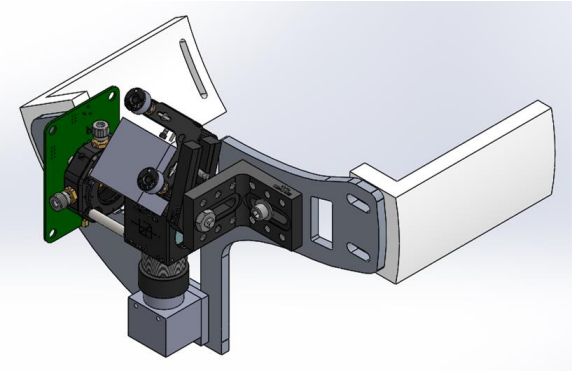
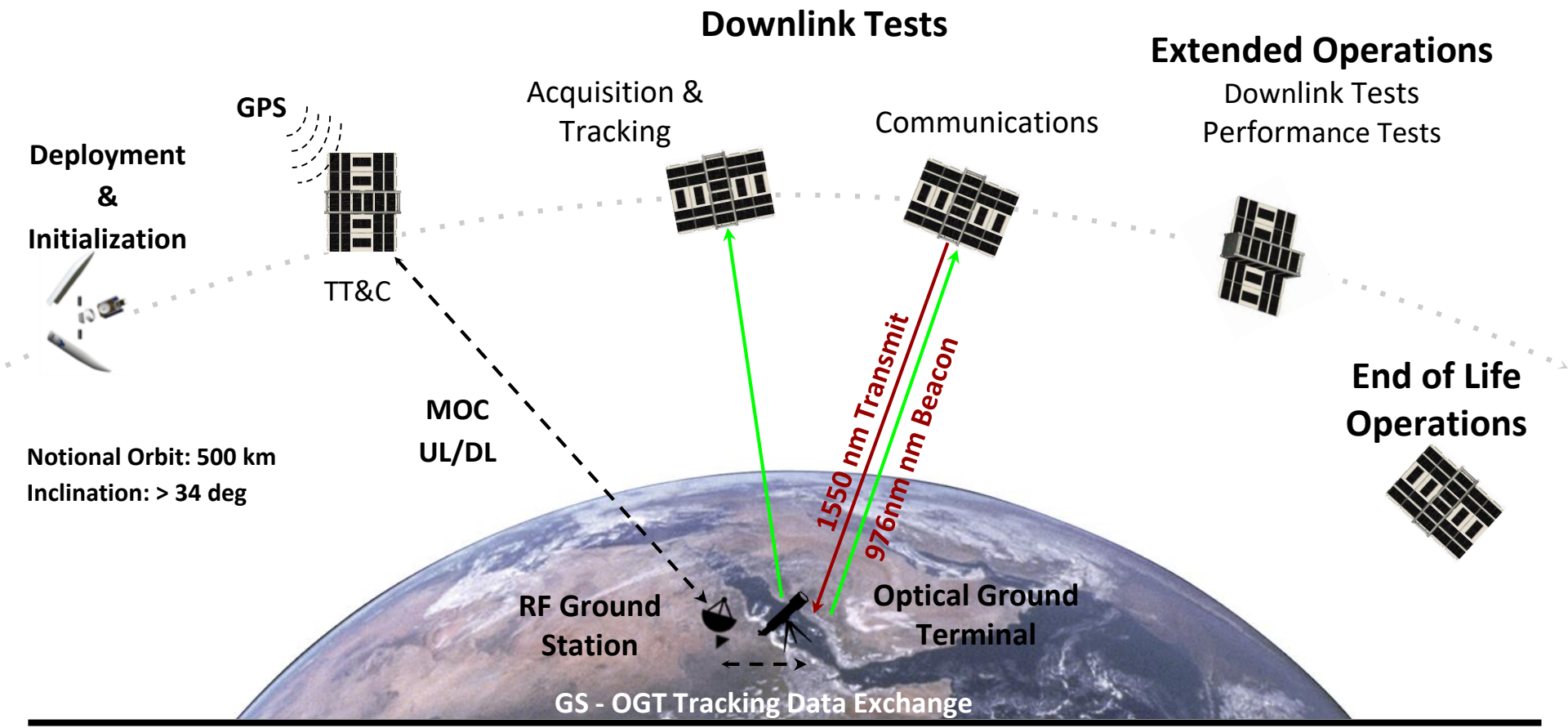
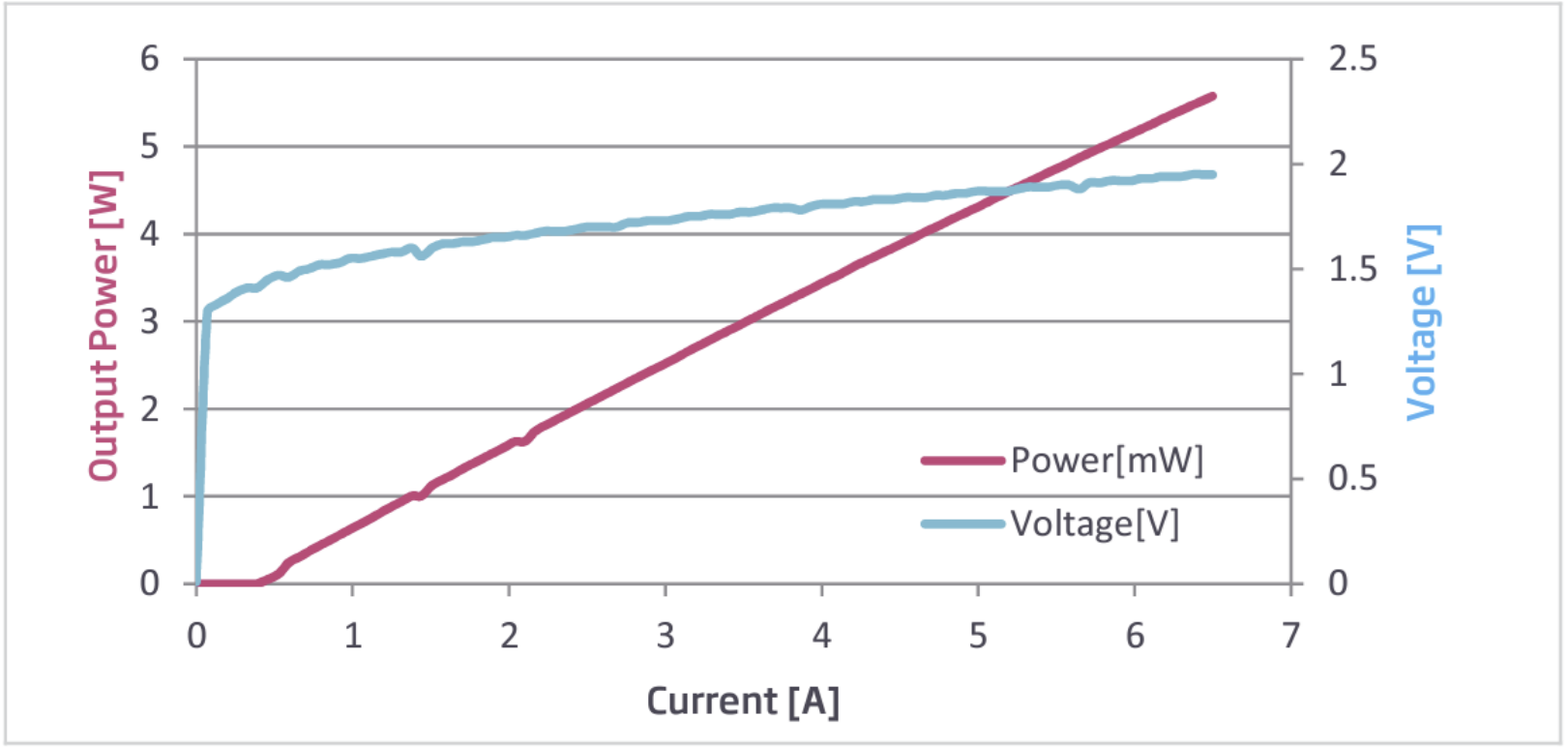


Image: T. Sevigny

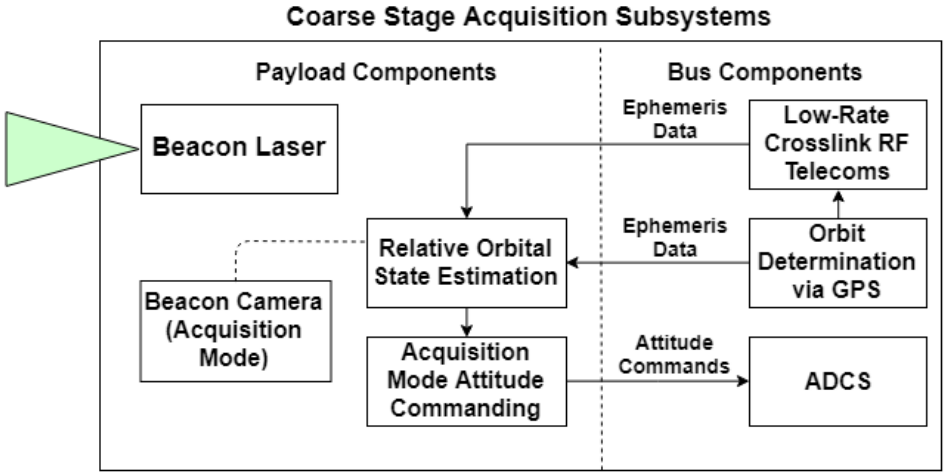
CLICK-A Concept of Operations

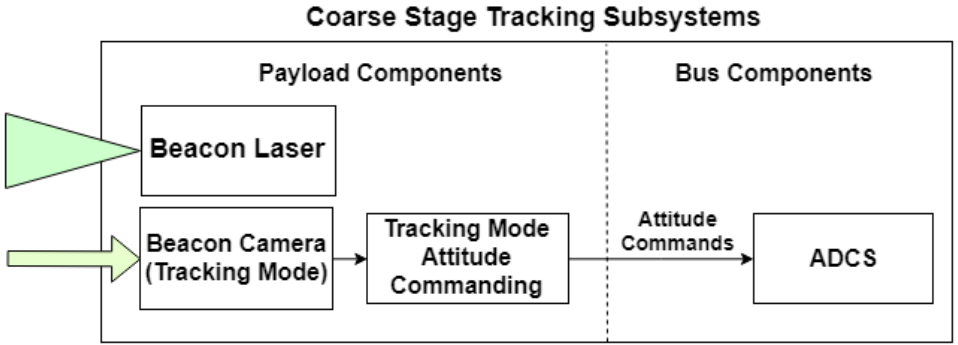


Beacon Laser Power Curve



CLICK B/C Coarse PAT





Images: P. Grenfell