Development of a pathfinder airborne mission to demonstrate a modular payload concept for Earth science: an upcoming stratospheric balloon flight and synergistic lidar and HAPS/HALE activities

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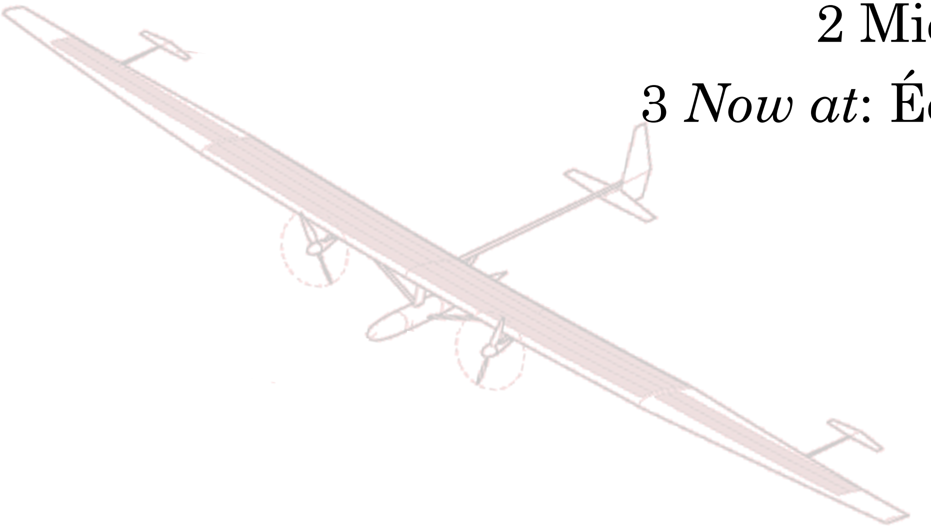

SOARS, 2024

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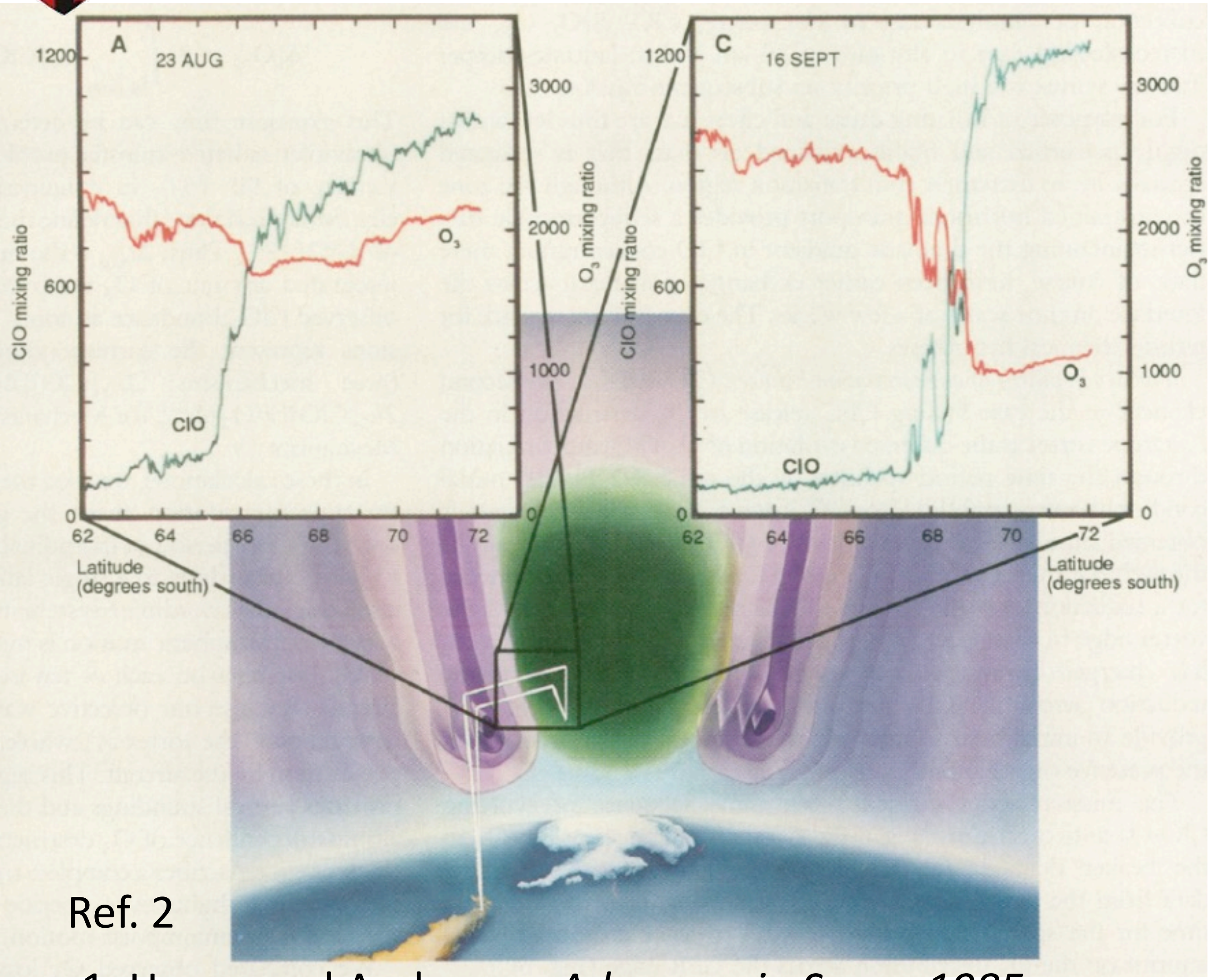
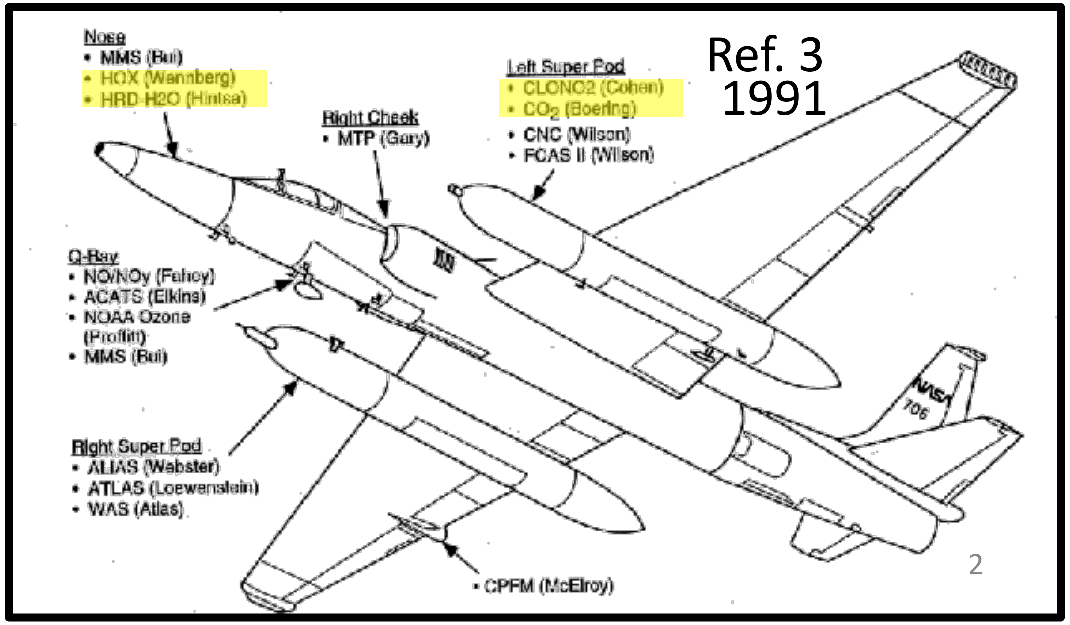
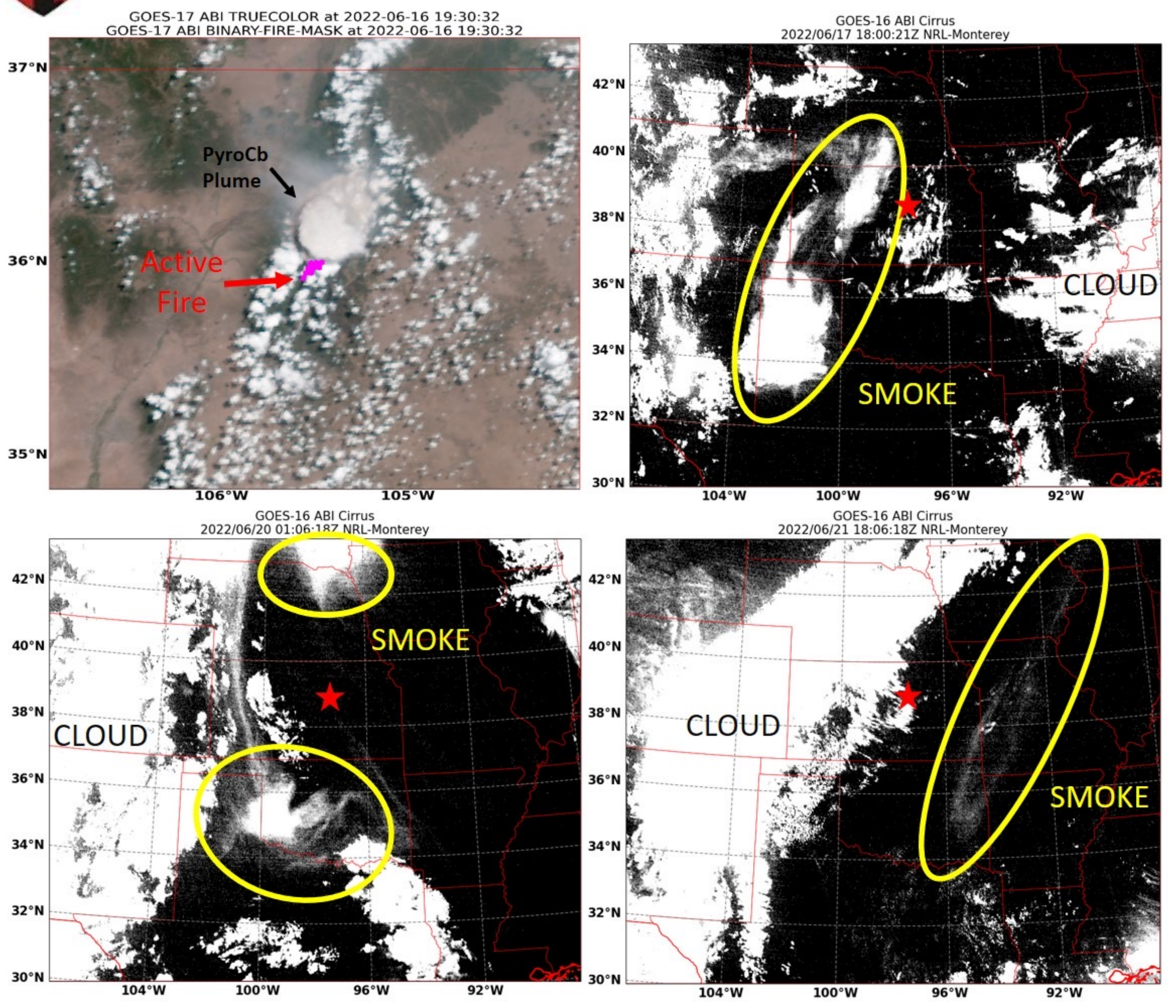
Harvard University heritage in stratospheric platforms and research



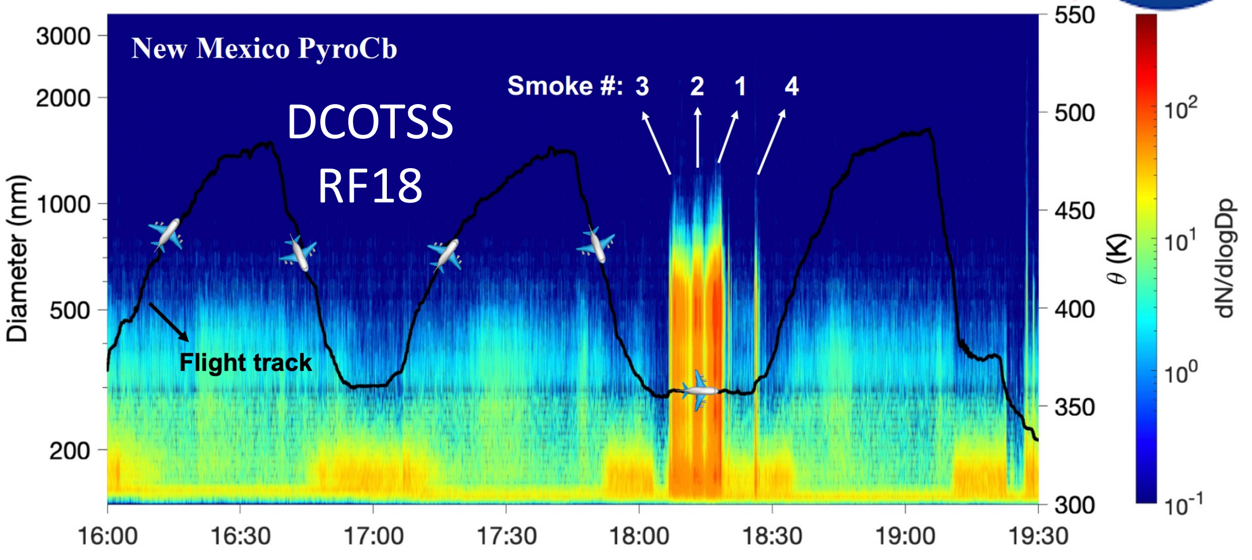


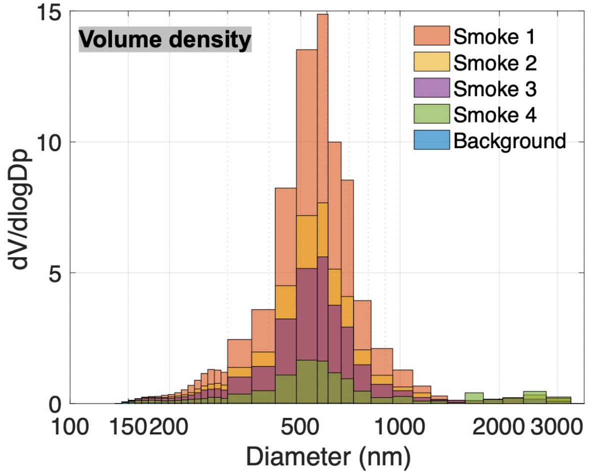
1. Hazen and Anderson. *Advances in Space 1985*
2. Anderson, Toohey, and Brune *Science* 1991
3. Stimpfle, R. M., et al. *JGR* (1999

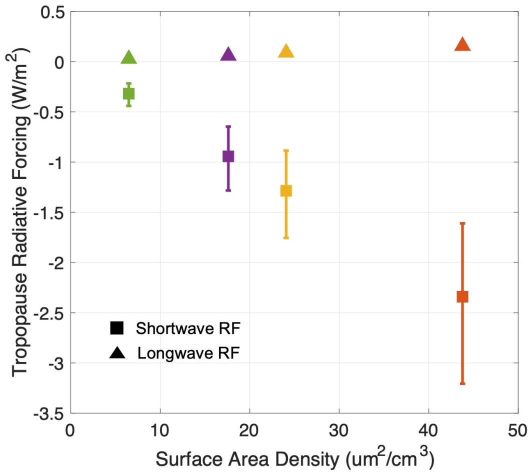
Satellite observations to process understanding: DCOTSS EVS-3 ER2 flights



Geostationary satellites provide continuous surveillance to pinpoint and follow smoke (credit: Dave Peterson/Mike Fromm NRL)







Airborne measurements of size distribution allow RF calculation, microphysics insights

HALE solar-powered aircraft platform

HALE Platform and Program

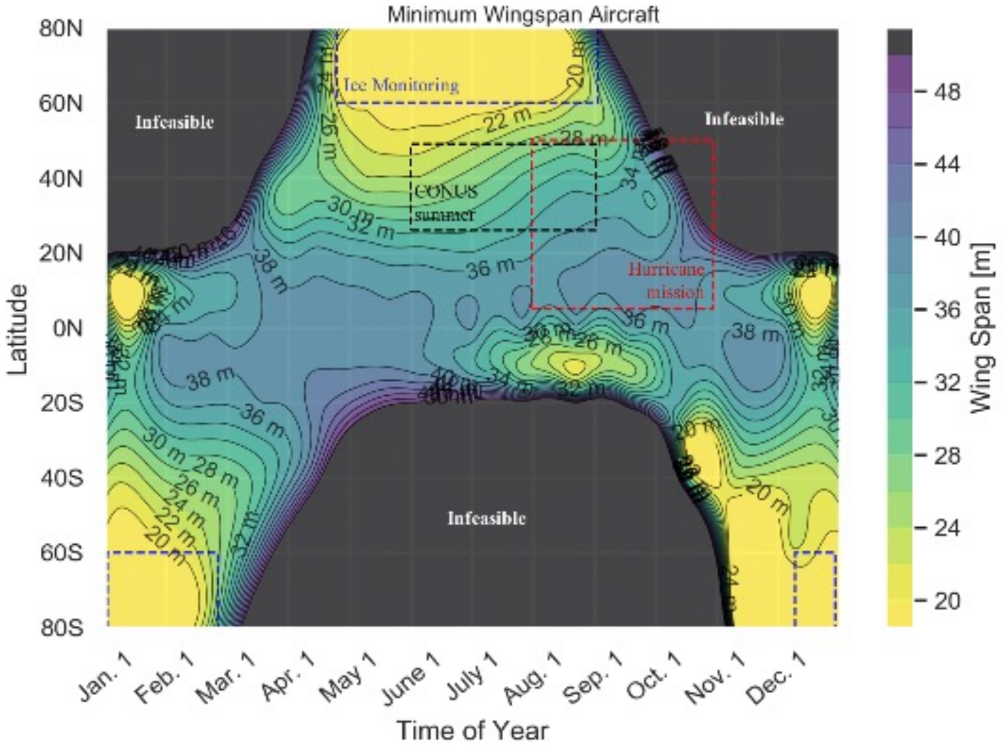
- Stratospheric Airborne Climate Observing System (SACOS) – partnership between Harvard University, Electra.aero, MIT
- Various scientific endeavors as initial use case
- Awarded NASA SBIR Phase 2 (among other funding)
- First flight of Demonstrator vehicle *Dawn One* achieved in September 2022
    - Aero-structural airworthiness of Objective vehicle – identical airframe and structural components
    - 90-foot wingspan with a TOGW of ~120 kg
    - Novel aerodynamic designs
    - Partial solar cell coverage including representative stack-up
- Upgrading subsystems to up-and-away flight through developments in propulsion, battery system, and solar cell systems

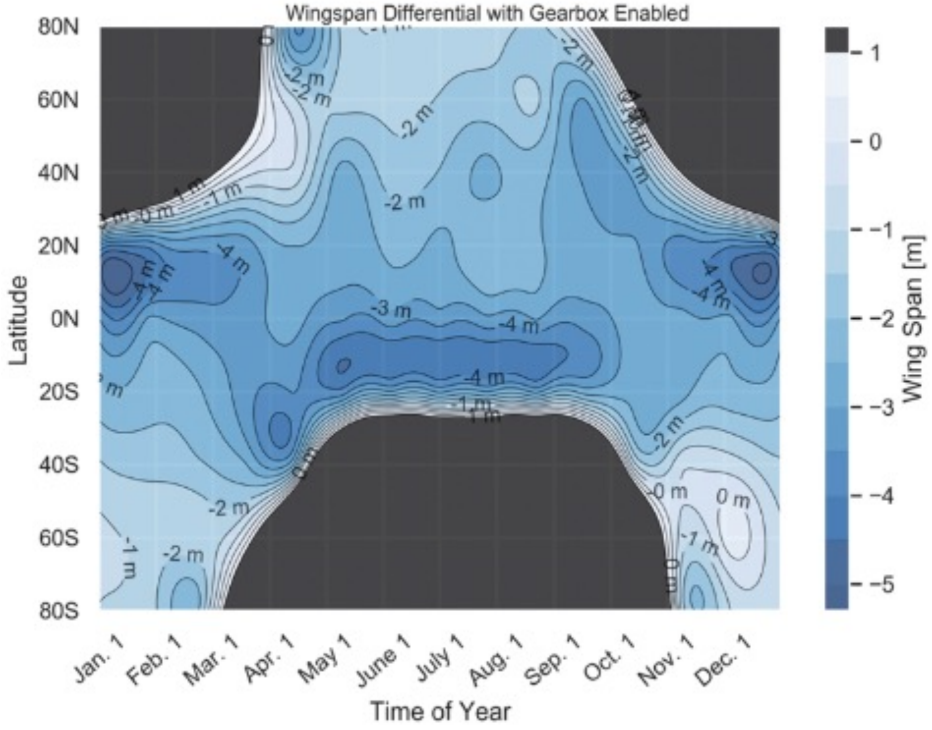
Dawn One during its first flight

Feasibility Analysis

Feasibility Maps

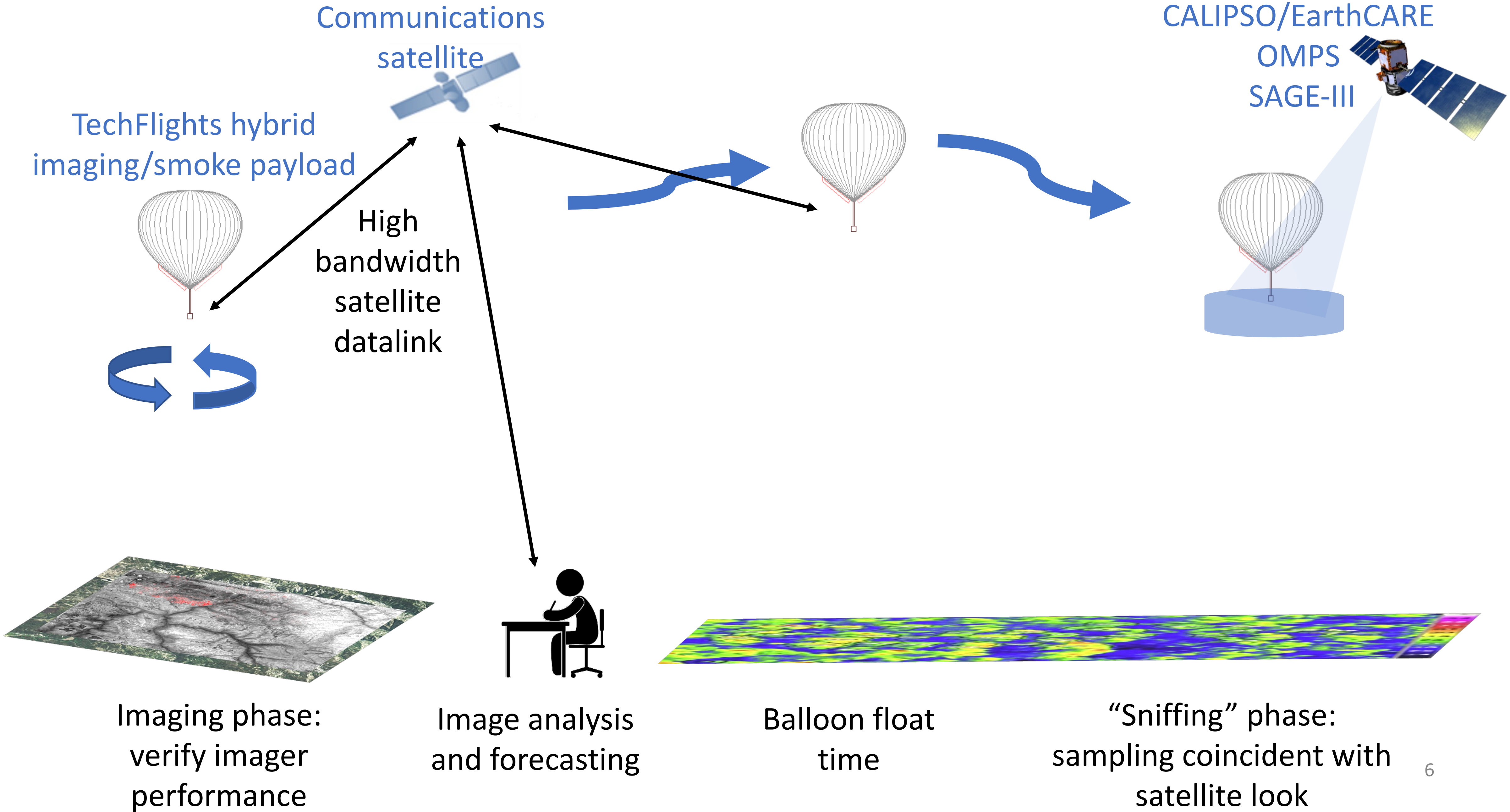
- Converged MDO mission-coupled aircraft designs demonstrate feasibility across geographical and temporal landscapes – set to objective function of wingspan minimization but can be configured for payload mass, power, or other performance functionality
- Allows for broad program management and understanding of capabilities, as well as determination of sensitivities to various parameters and variables



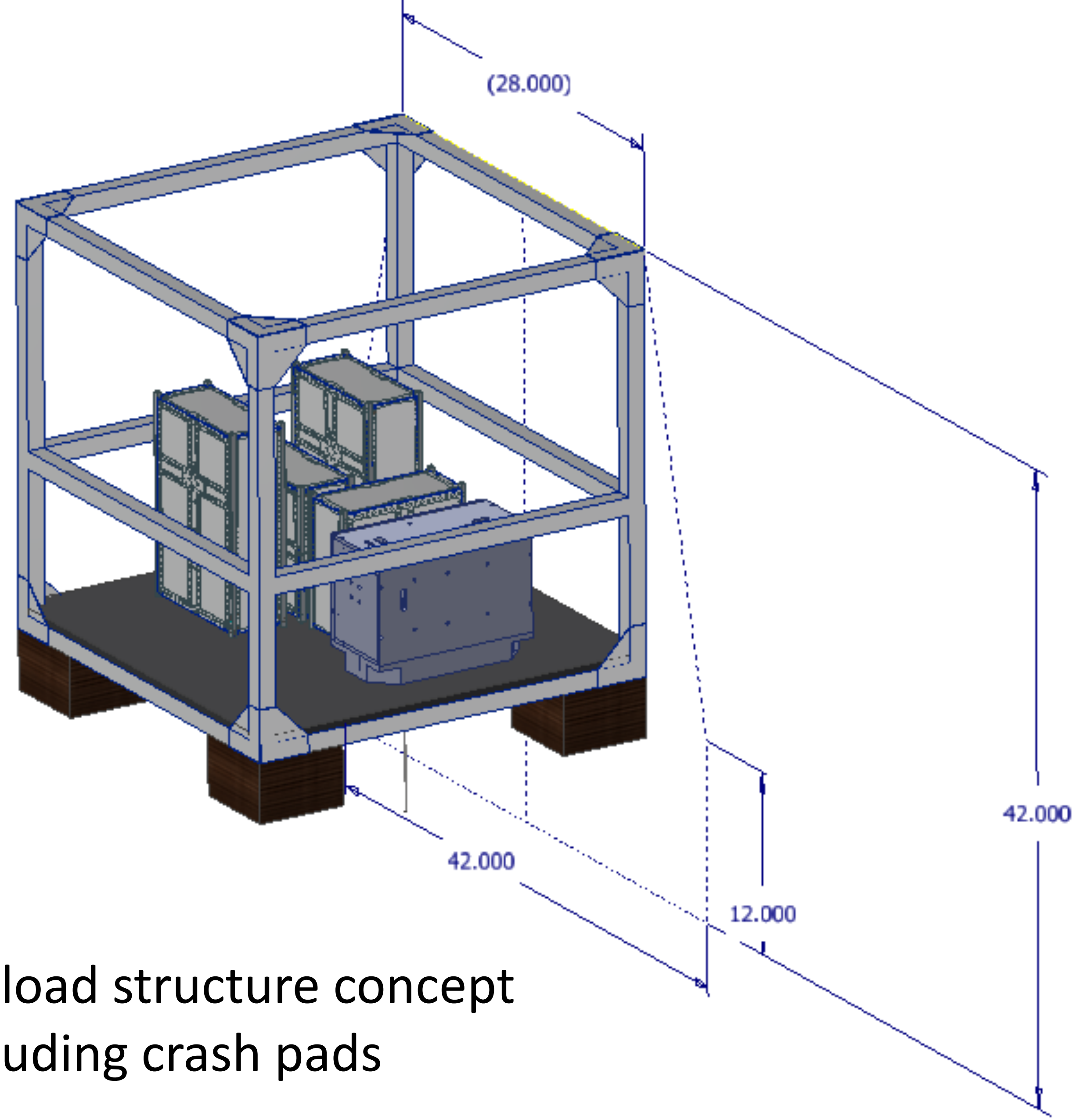


Mascarenhas, Craig A., James G. Anderson, and John S. Langford. "Solar-Aircraft Feasibility Analysis Based on Propulsion System Characteristics." *AIAA AVIATION 2022 FORUM*. 2022.

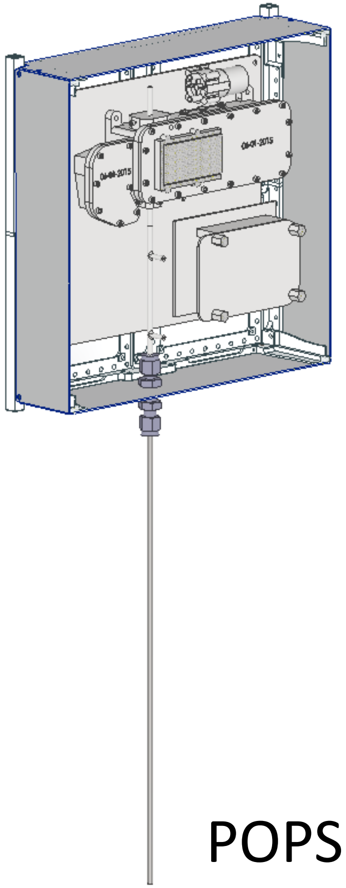
Multi-platform Interface Demo on HAPS



Zero-Pressure Balloon Payload Concept

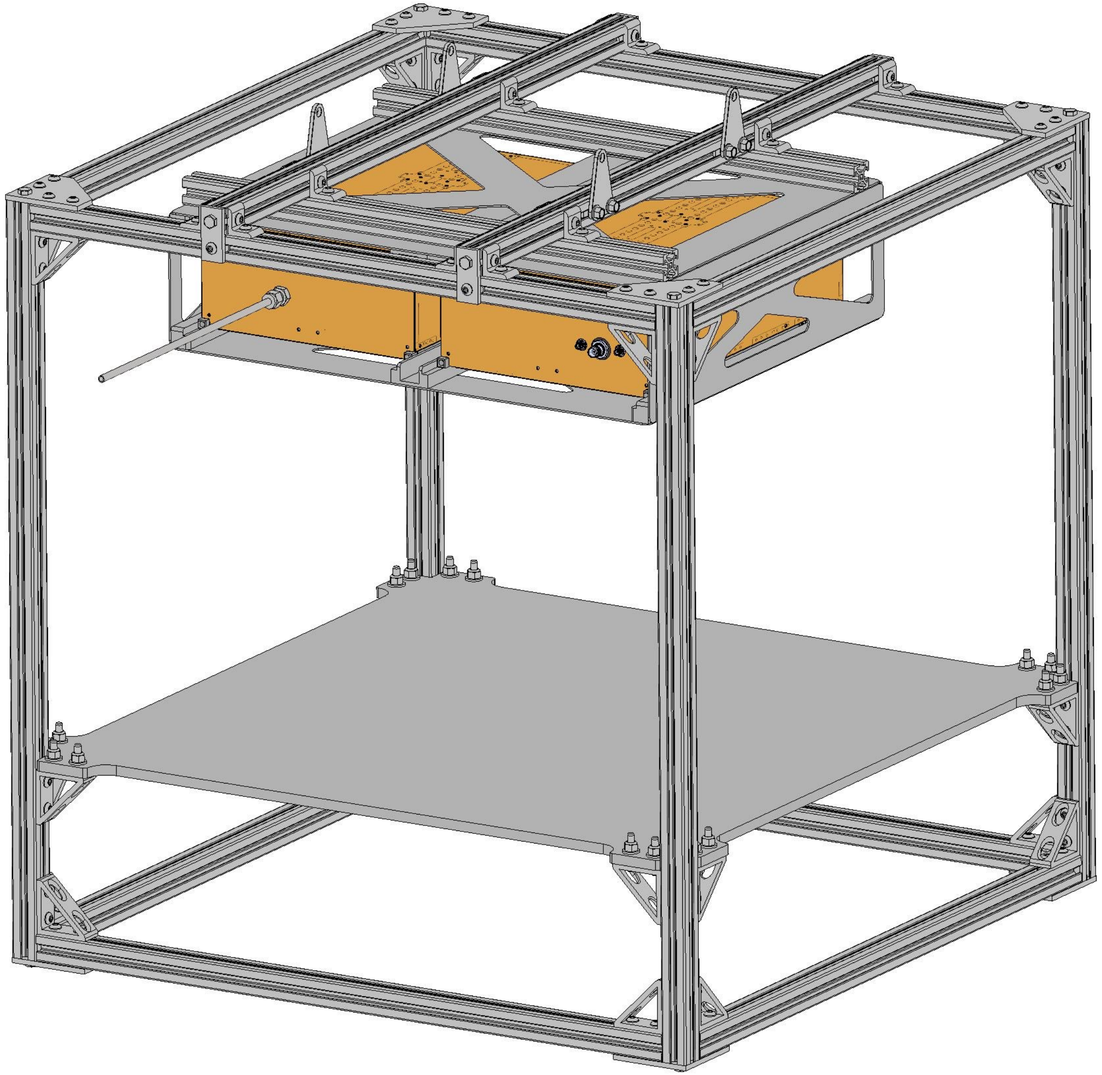


Payload structure concept including crash pads



POPS instrument (smoke "sniffer") in multi-platform chassis with inlet

Zero-Pressure Balloon Payload Concept (2)

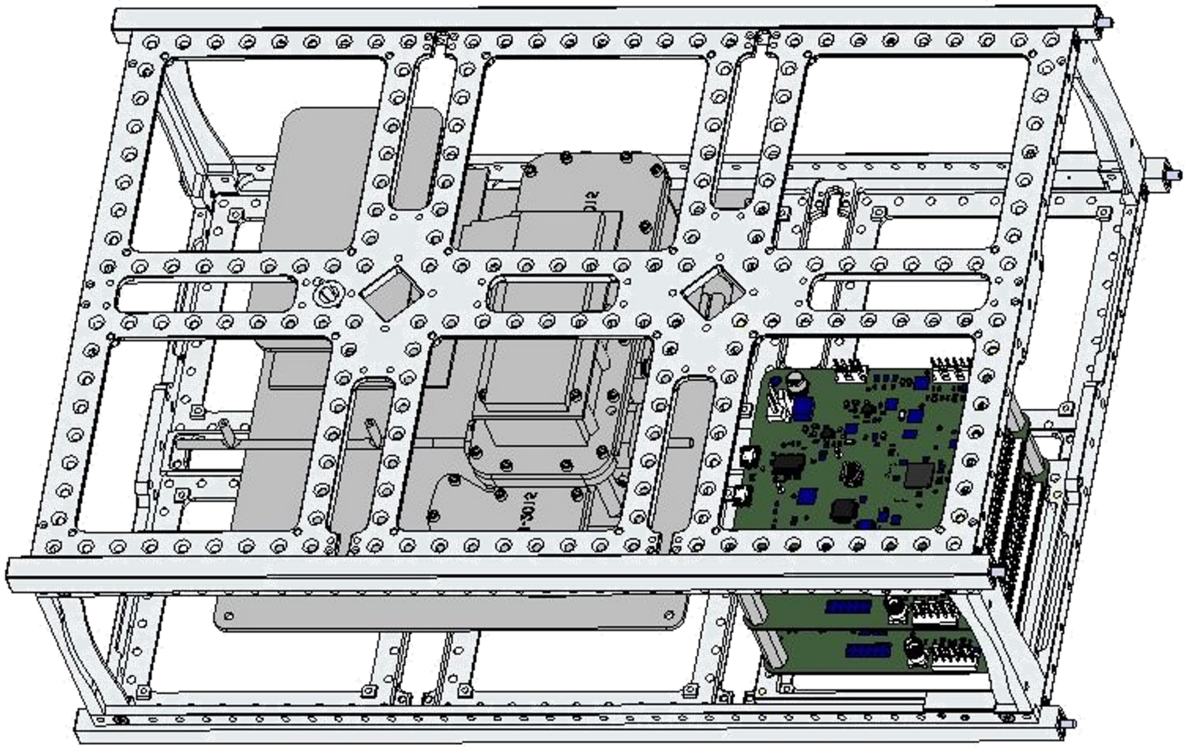


Payload design for Harvard equipment

- Payload re-designed to orient POPS correctly for conventional ZP balloon
- Rail system for Cubesat chassis installation/removal shown
- Maximum flexibility for additional payload

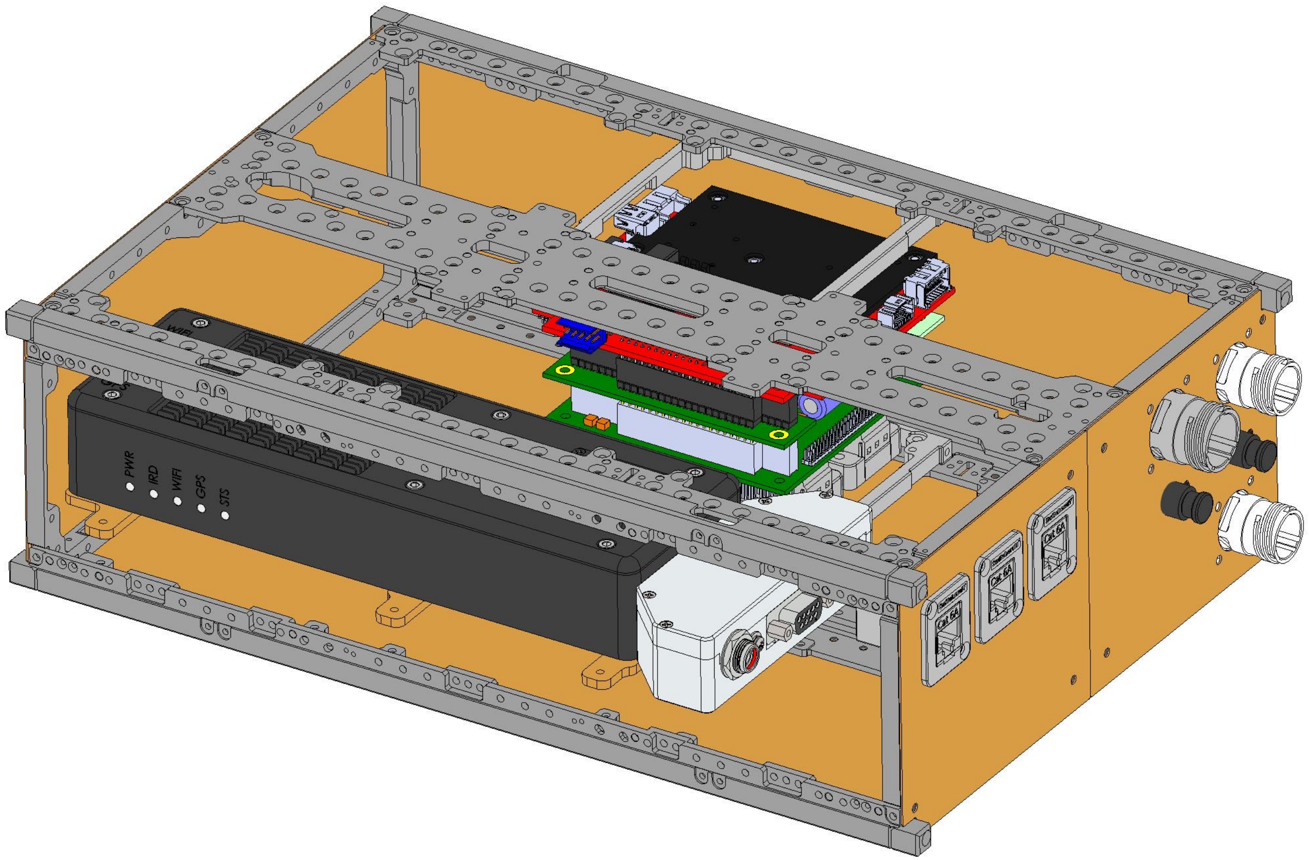
Zero-Pressure Balloon Instrument Design

- Smoke instrument integrates into standard 6U Cubesat chassis
- Includes notional electronics:
  - DC/DC power conversion
  - Power distribution
  - Ancillary I/O and comms

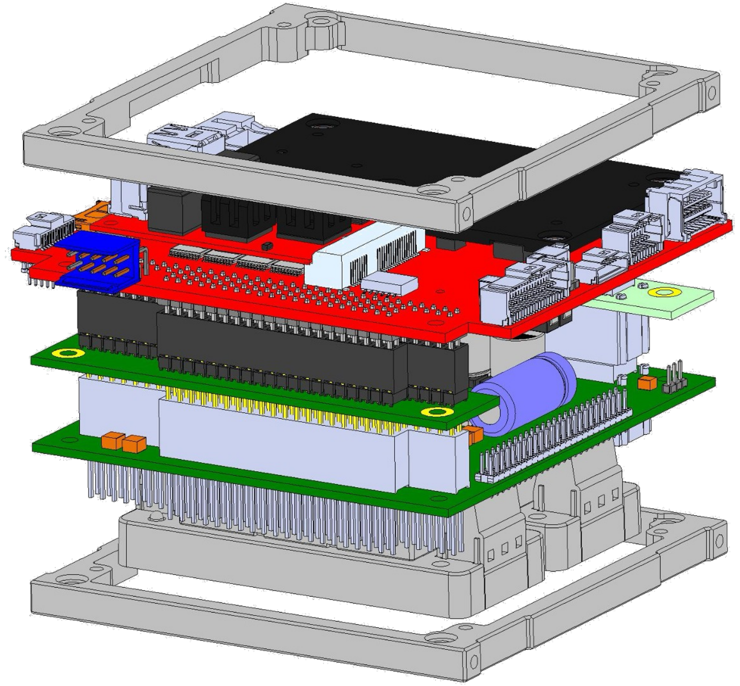


* Shown with an available CAD model from an existing manufacturer for informational purposes

Zero-Pressure Balloon Comms/Data System Design



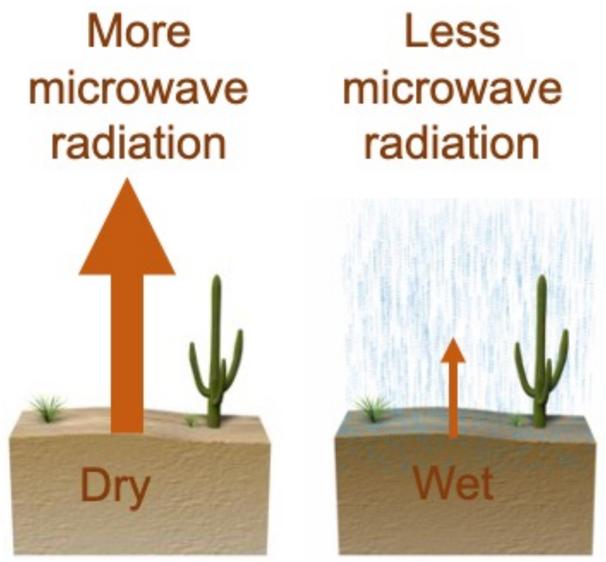
Satellite datalink, single board computer, power conditioning/distribution



Stack view

Why Differential Absorption Lidar (DIAL) so compelling?

Thermodynamic State of the Atmosphere



- Wildfire risk (VPD)
- Extreme weather
- Dominant climate uncertainties
- Air quality
- Carbon cycle and eco-systems

Atmospheric Composition

- Applicable to O_3, SO_2, NO_2, NO, NH_3, CH_4, CO_2, Hg, VOCs, toluene, benzene
- High selectivity, high precision
- Applicable to both earth science and planetary science
- Airborne, ground-based, spaceborne

All-Semiconductor Lidar on HALE solar-powered aircraft

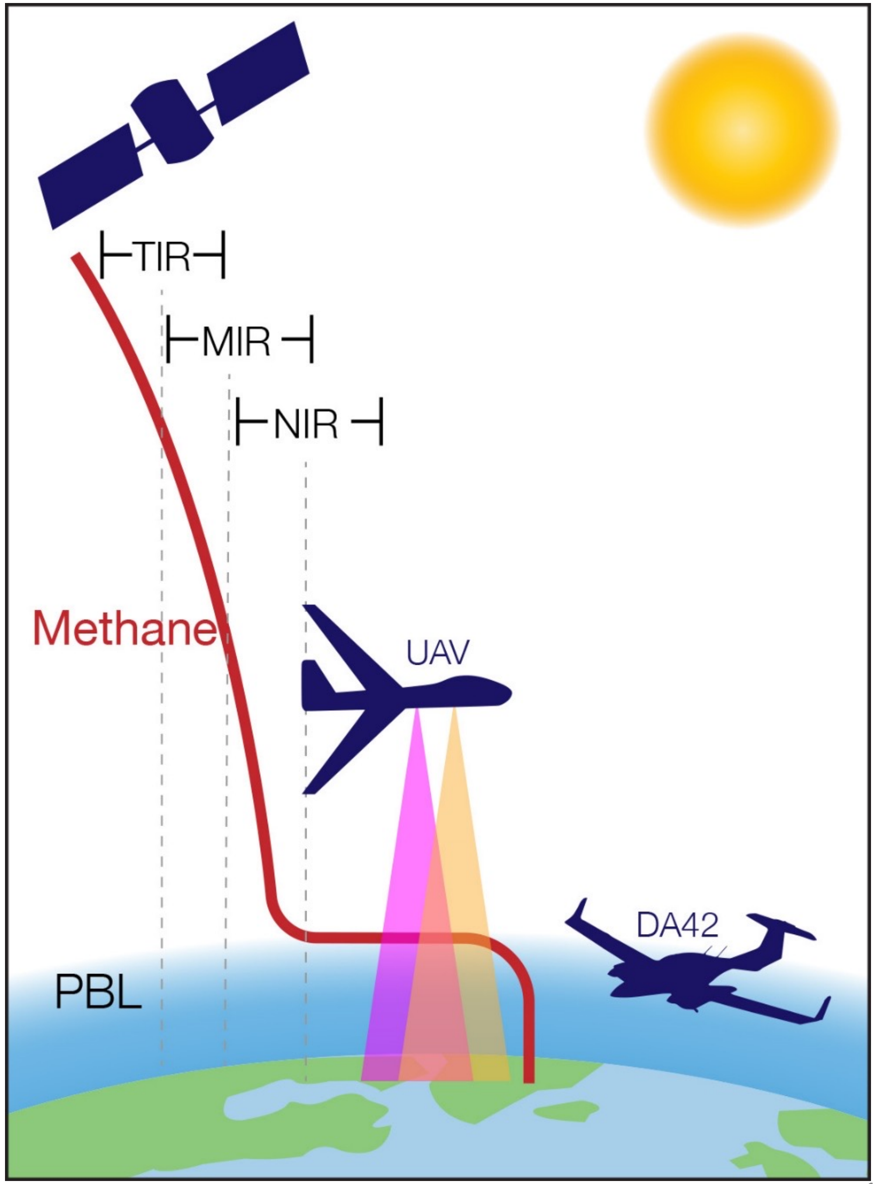
Table 1. Envisioned Operating Parameters of the PWV IPDA Instrument

Parameter	Resolution Focus	Precision Focus
Operating altitude	20 km	20 km
Integration time (per line)	150 ms	3.3 s
Averaged number of shots	1124	24,700
Platform speed	30 m/s	30 m/s
Horizontal resolution	10 m	200 m
Range precision resolution	10 m	100 m

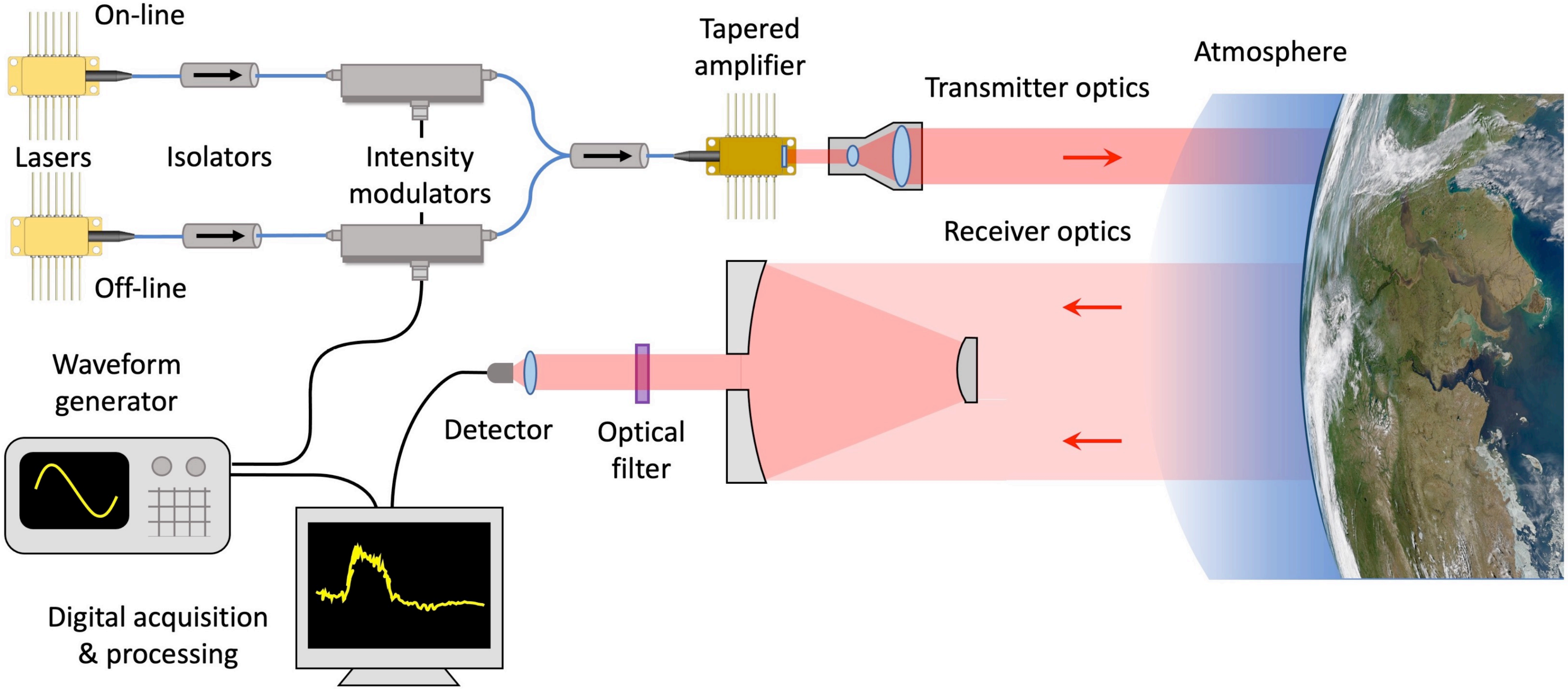
Table 4. Example PWV IPDA Platform Design and Operational Parameters

Operating altitude	65,000 ft
Wingspan	20 m
Aircraft mass	132 kg
Payload mass	12 kg
Payload power	120 W
Continuous operation	5 months

†Dykema, J. A., †Bianconi, S., Mascarenhas, C., & Anderson, J. (2023). Feasibility study of a total precipitable water IPDA lidar from a solar-powered stratospheric aircraft. Applied Optics, 62(25), 6724-6736.



Block Diagram for All-Semiconductor IMCW PWV IPDA



Schematic of the envisioned PWV IPDA lidar instrument based on an all-semiconductor MOPA transmitter and bi-static optics configuration. A compact collimated tapered amplifier is used to amplify both the online and the offline sources. The incoherent receiver records the time-resolved intensity of the return echo and the matched filtering is performed in the digital domain by a compact DAQ system.

PWV Simulation results

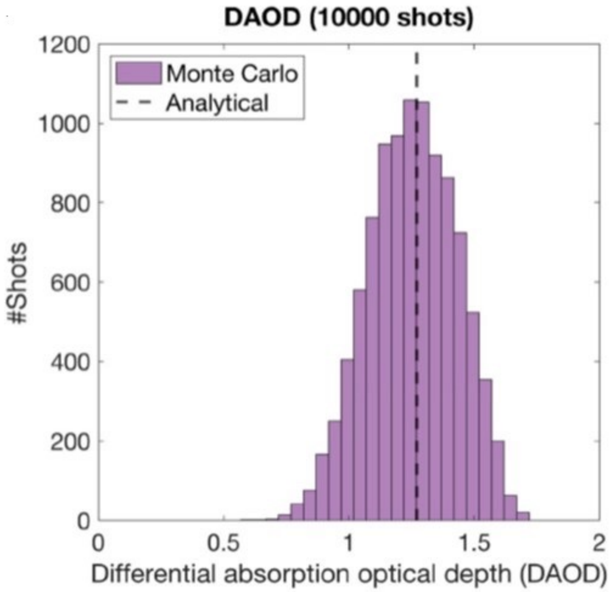


Table 6. Representative Calculations of Other Error Sources

Error Source	PWV Precision (mm)	PWV Bias (mm)
Atmospheric backscatter	3.31	–
Thin cloud	6.87	–
Dry atmosphere	–	−1.71
Wet atmosphere	–	2.58
Dry layer	–	−1.98

Table 5. Total Precipitable Water and Selected Optimal Online for Selected Atmospheric Models

Atm. model	PWV[a] [mm]	λ_{opt} [nm]	E_{gnd}[b] [cm^{-1}]	2-Way Trans.[b]	2-Way DAOD[b]	SNR[b]	PWV Prec.[b] [mm]
MLS	28.6	813.23	3315.5	0.27	1.28	0.217	3.23
MLW	8.38	815.70	3762.8	0.25	1.36	0.201	0.95
SAS	20.4	812.91	3310.7	0.29	1.22	0.228	2.30
SAW	4.09	815.68	2364.4	0.29	1.24	0.226	0.46
TRO	40.5	813.34	3343.7	0.27	1.28	0.216	4.57
USA	13.8	815.70	3569.4	0.29	1.21	0.228	1.56

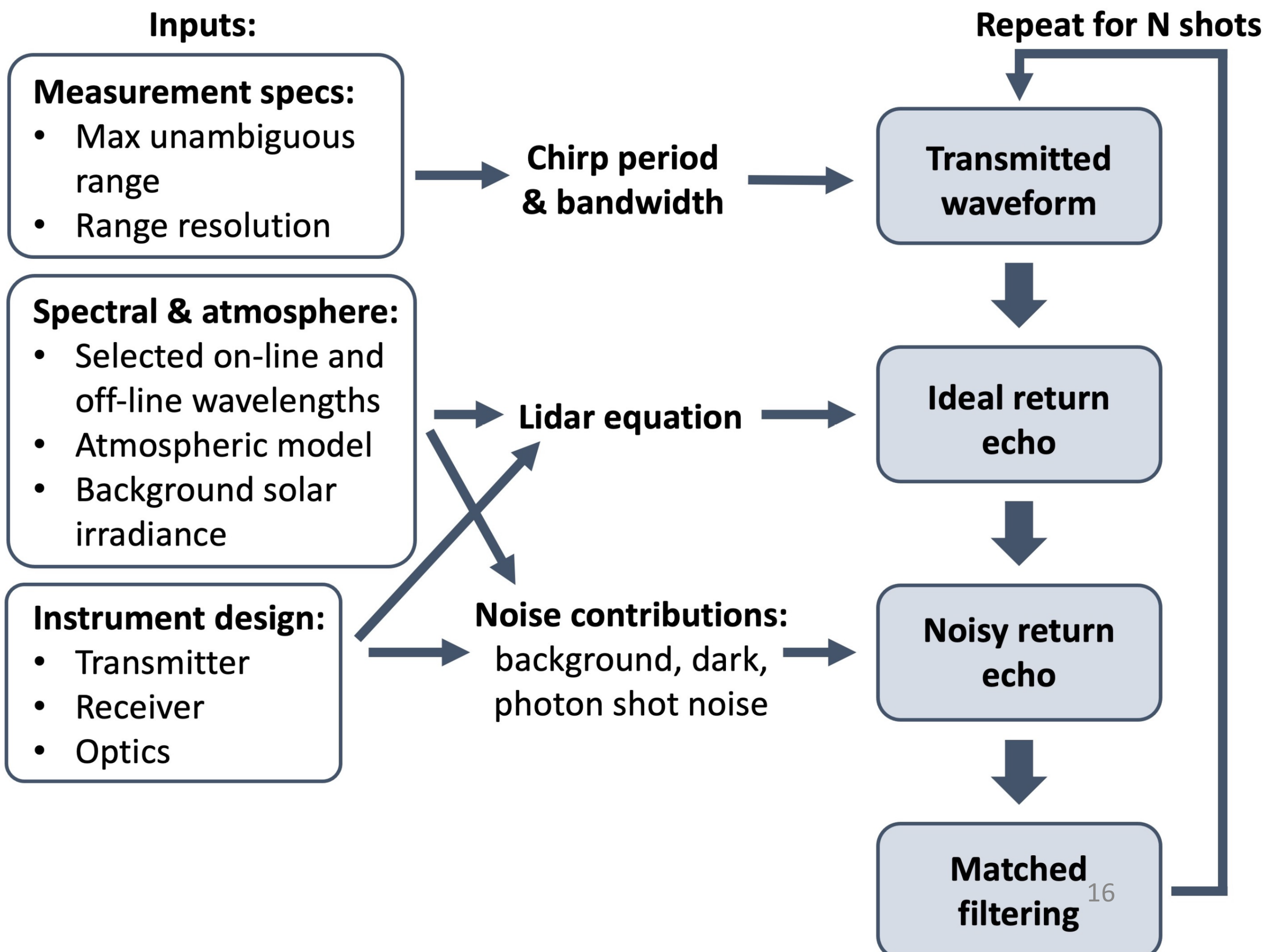
[a]In a 20 km column.
[b]At λ_{opt}.

Acknowledgements

- Thanks to Mike Greenberg and Norton Allen of Harvard University
- Thanks to NASA STMD’s Flight Opportunities program for supporting high-altitude balloon flight test and payload development

Monte Carlo Simulation of PWV SNR for Model Atmospheres

Block diagram of algorithm used for Monte Carlo modeling of the PWV IPDA precision using IMCW range encoding scheme and matched filtering. The input parameters in the boxes on the left sides are related to the main computational steps of the algorithm each steps and their relation. The main computational steps of the algorithm are represented by the colored blocks on the right side and the boxes and arrows on the left side represent the corresponding input parameters and governing equations.



TPW Source and System Parameters

Wavelength range	812-816 nm
Output power (CW)	2 W
Beam quality	$M^2 = 2$
Beam divergence	0.1 mrad
Beam expansion	x10
Laser line width	500 kHz
Wall-plug efficiency	>15%
Modulation chirp bandwidth	1.5 MHz
Chirp duration	133 µs

Lidar Source Parameters

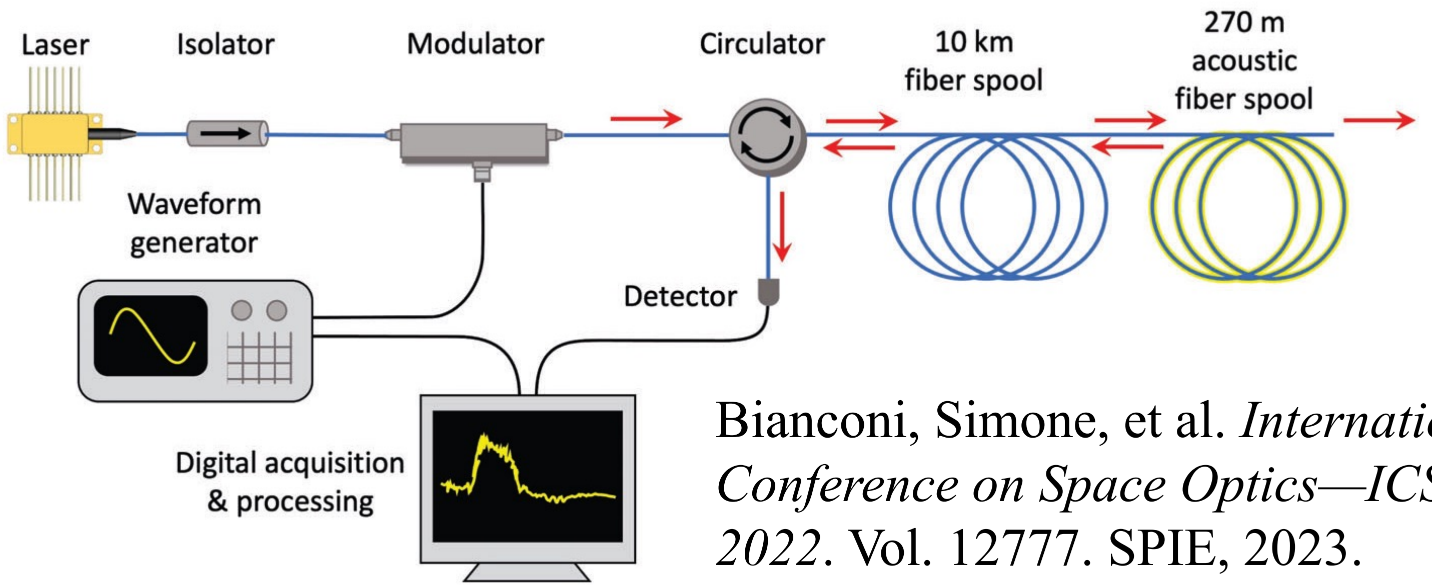
Optical efficiency	80%
Telescope diameter	150 mm
Telescope field of view (FoV)	50 µrad
Optical bandpass filter width	1 nm
Detector NEP	0.9 fW $Hz^{1/2}$
Detection bandwidth	1.5 MHz
Detector quantum efficiency (QE)	77%
Detector responsivity	128 A/W
Detector active diameter	0.5 mm
Detector operating temperature	253 K
Geometric overlap at max range	1.00
Background solar irradiance	1.3 W m^{-2} nm^{-1}

Lidar System Parameters

Laboratory Evaluation of IMCW Concept

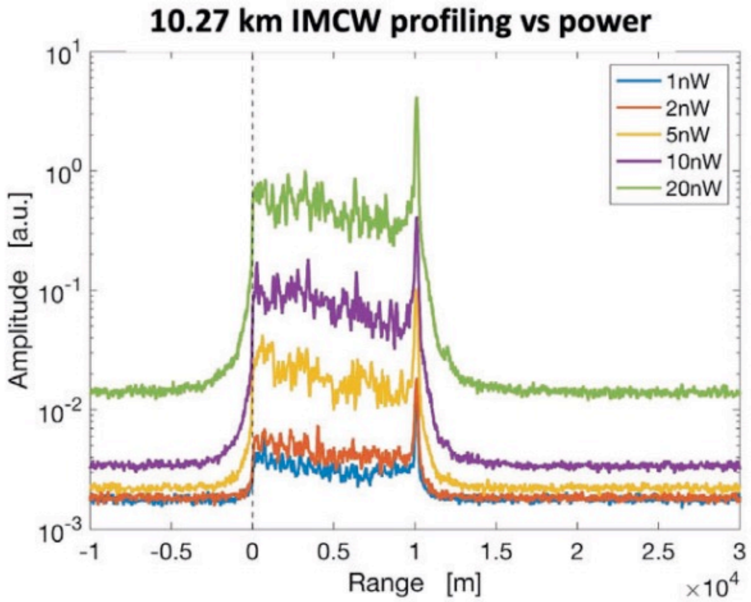
- IMCW ranging can be implemented using benchtop experiments with a fiber-optic delay line

- **Goal:** risk reduction by lab-based system development and model validation

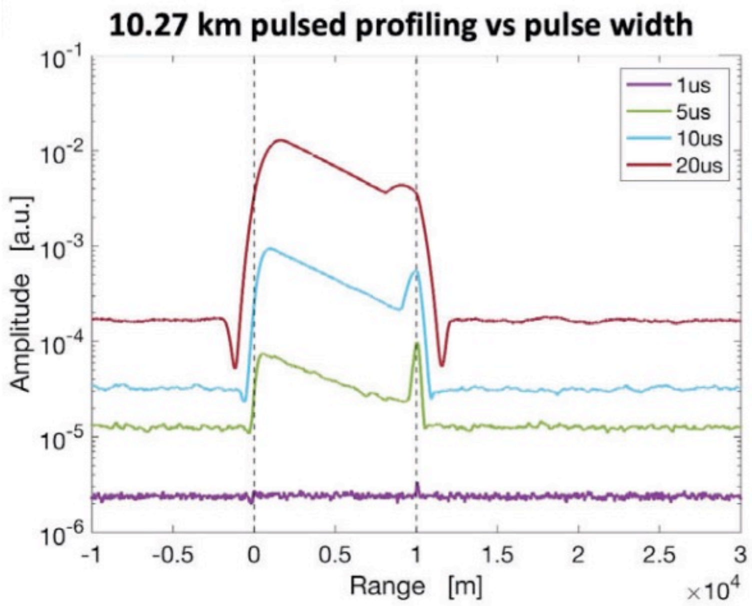


Bianconi, Simone, et al. *International Conference on Space Optics—ICSO 2022*. Vol. 12777. SPIE, 2023.

IMCW Fiber Result



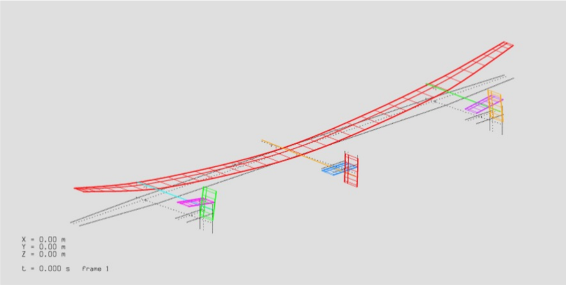
Pulsed Fiber Result

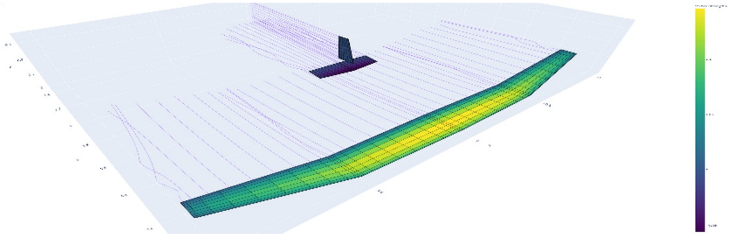


Multi-disciplinary Optimization

Integrated Approach in the MDO

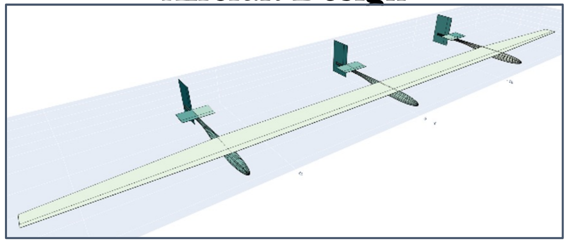
- Trajectory optimization and utility of quantitative payload understanding
- In addition to optimized designs, custom manual inputs from real-world design and canvassing such as custom propeller and airfoil design, electric motor data, etc.



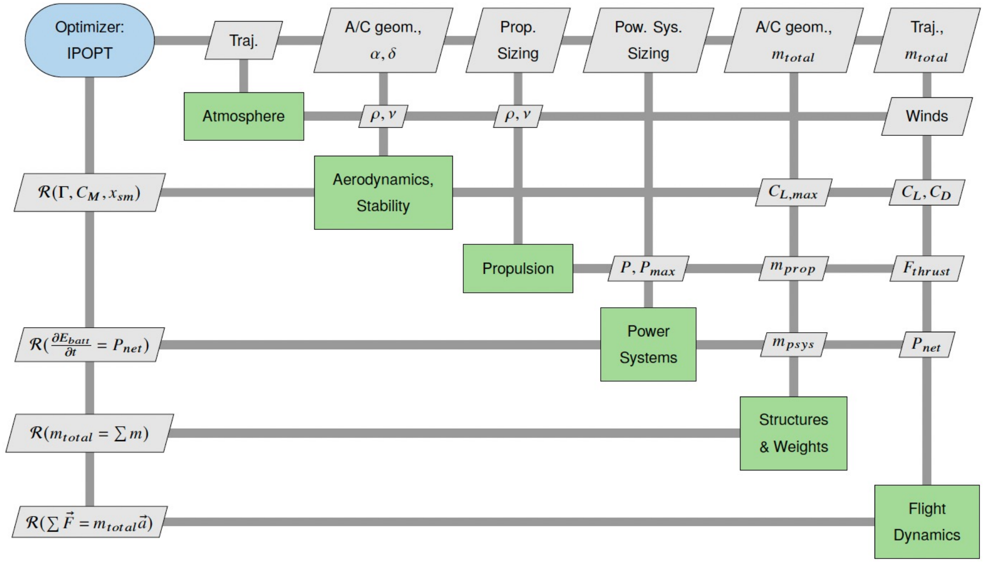


Simultaneously optimizing...

Aircraft Design



Mission Profile



Variables

Hundreds, including:

- *wing geom. (two-sect.),*
- *tail geom. (one-sect.),*
- *boom length,*
- *propeller diam.,*
- *battery cap.,*
- *solar panel area,*
- *motor rated power,*
- *wing internal struct.*

Parameters

- *payload mass*
- *# of booms*
- *battery spec. energy*
- *margins*

Variables

Thousands, including:

- *altitude*
- *airspeed*
- *throttle, ctrl. surf. inputs*

Parameters

- *min. altitude*
- *wind speed dist.*
- *latitude*
- *day of year*

Objective Function

Minimize wingspan (not TOGW!)

Constraints

Physics models

- *150 models, 4,000 constraints*

Peter D. Sharpe, Annick J. Dewald, and R. John Hansman. "An Optimization Approach to Mapping the Feasible Mission Space of a High-Altitude Long-Endurance Solar Aircraft." *AIAA AVIATION 2021 FORUM*. 2021.