Stratospheric HALE Radar for STV

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Abstract

Aloft Sensing, Inc. (Aloft) is developing a breakthrough compact radar system for deployment on high-altitude long-endurance (HALE) stratospheric platforms. These emerging platforms offer the unmatched ability to persistently observe science targets and capture the dynamics of rapidly evolving surface vegetation and topographic phenomena. Aloft's radar system is specifically designed to overcome the challenges associated with synthetic aperture radar (SAR) and interferometric SAR (InSAR) operation from these platforms in the stratosphere, maintaining coherence over the minutes-long collection apertures and tolerating the non-linear flight trajectories to generate high-quality imaging and interferometric products. The large fractional bandwidth of Aloft's radar system, combined with innovative motion compensation techniques, enable high-precision repeat-pass interferograms to be generated despite the coarse trajectory control of HALE platforms. Furthermore, Aloft's patent-pending positioning, navigation, and timing (PNT) technique supports coherent multistatic operations, such that a new type of cross-platform interferometric and volumetric radar products is possible. This presentation describes the current state of Aloft's payload development and demonstrates, via system performance models, that millimetric surface changes, centimetric topography, and decametric volumetric resolutions can be obtained from this 7 kg HALE radar system.

Stratospheric HALE Radar for STV

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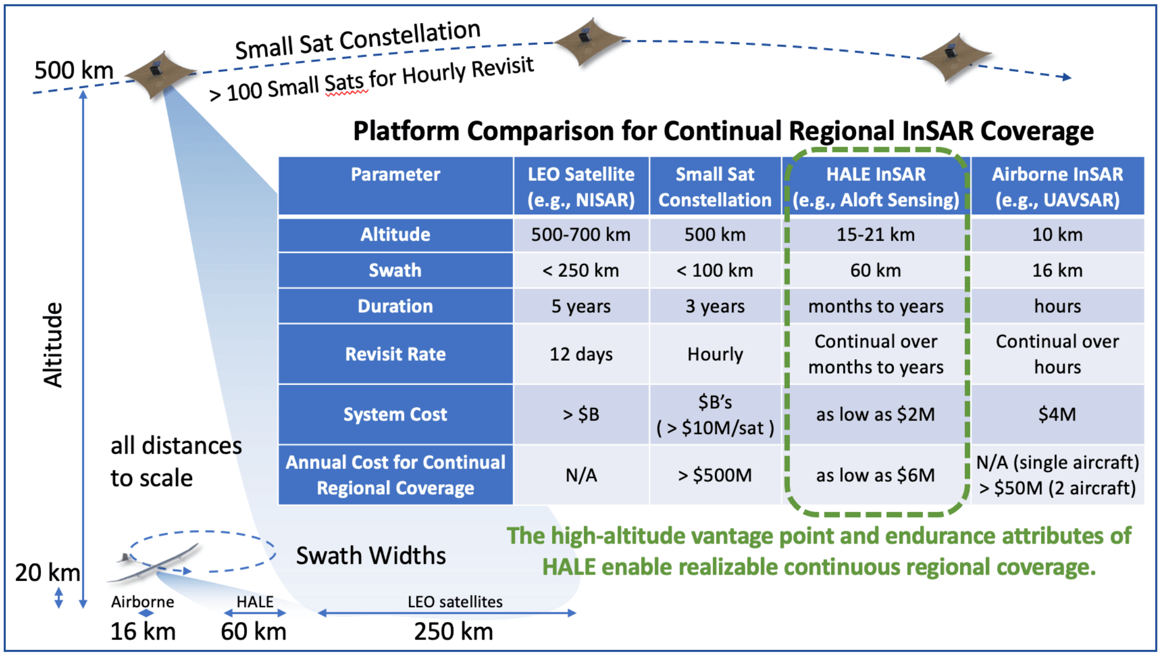
PRESENTED AT:

HALE PROVIDES CONTINUOUS AND COST-EFFECTIVE REGIONAL COVERAGE

Emerging High-Altitude Long-Endurance (HALE) platform technologies offer the **unmatched ability to persistently observe science targets** and capture the dynamics of rapidly evolving surface vegetation and topographic phenomena. Their stratospheric vantage point provides wide-area coverage and their endurance and station-keeping attributes promise cost-competitive continuity, especially in comparison to small satellites and airborne vehicles.



Parameter	LEO Satellite (e.g., NISAR)	Small Sat Constellation	HALE InSAR (e.g., Aloft Sensing)	Airborne InSAR (e.g., UAVSAR)
Altitude	500-700 km	500 km	15-21 km	10 km
Swath	< 250 km	< 100 km	60 km	16 km
Duration	5 years	3 years	months to years	hours
Revisit Rate	12 days	Hourly	Continual over months to years	Continual over hours
System Cost	> $B	$B's (> $10M/sat)	as low as $2M	$4M
Annual Cost for Continual Regional Coverage	N/A	> $500M	as low as $6M	N/A (single aircraft) > $50M (2 aircraft)

While conventional spaceborne and airborne synthetic aperture radar (SAR) and interferometric SAR (InSAR) approaches provide well-resolved and spatially dense maps of surface change and topography, and potentially vegetation, they inadequately address the low-latency and rapid-revisits required to effectively answer critical STV science questions. Constellations of SAR/InSAR satellites that support daily revisit rates have been proposed to reach the desired level of persistence, but the number required (> 100) and the **associated costs quickly become prohibitive**, even for small-satellite-based architectures. Crewed and uncrewed airborne systems involve **complex logistics and costs** that, with their **limited coverage area**, often preclude the sustained wide-area collection campaigns necessary to capture and be responsive to events on the ground.

The emerging class of near-space high-altitude long-endurance (HALE) platforms that includes high-altitude balloons, airships, and solar-powered remotely piloted aircraft offers the potential for ***low-cost continuous InSAR and distributed sensing*** with sub-hourly temporal updates. By persisting for weeks and months in the stratosphere high above a science target, these platforms enable an InSAR sensor to stare and continually map the surface deformations and topographic changes multiple times per hour. Further, the smaller and lower-cost HALE platforms can be readily proliferated into a regional mesh network to achieve the distributed coherent sensing that many STV observables require.

HALE platforms vary in cost, navigation ability, station-keeping capability, and SWaP capacity. The combined set of attributes dictate the affordability and practicality of certain types of measurements. For example, airship technologies can be very expensive on a per-unit basis, but their extremely-high SWaP capacity supports payload ride-sharing, and their **years-long endurance reduces the mean service cost**. Additionally, airships' **higher SWaP capacity** supports flexible payload mounting configurations, allowing for singe-pass multi-baseline interferometry. These platforms are appropriate for STV missions that can leverage non-targeted collections-of-opportunity and applications that require single-pass sensitivities. Smaller HALE platforms, on the other hand, are more severely SWaP constrained, but their **lower unit cost supports distributed sensing configurations**, as well as use cases that require rapid and flexible deployment.

Comparison of HALE Platform Class Performance

HALE Platform Class	Unit Cost†	Monthly Cost††	Service Lifetime	Navigation	Station Keeping	Payload Capacity	Example Vendors
Altitude-Controlled Balloons (large)	Low ($200K)	> $12M*	Single use	Limited	Limited	50+ kg, 150 W	Raven Aerostar, WorldView
Solar-Powered Aircraft (large)	High ($10-15M)	$1-3.5M	years	Very Good	Good	50 kg, 150-250 W	AeroVironment, BAE, Boeing, Airbus
Solar-Powered Aircraft (Small)	Low ($2-3M)	$0.5M	months	Very Good	Good	5-10 kg, <300 W	Swift Engineering, Kea Aerospace
Airships	High ($15-20M)	$1.5M	years	Very Good	Excellent	<300 kg, 9+ kW	Sceye

†Order-of-magnitude estimates are based on market study; pricing information is not publicly available.
††For 24/7 continuous coverage under a commercial service model. Estimates based on market study.
*A balloon's ability to keep station (or stay within 100 km of scene) varies with geography and season. Generously assuming 12 hrs of station keeping on average, 60 balloons are required to maintain continuous custody of the scene for 30 days.

Achieving the benefits of HALE-based SAR/InSAR/Distributed-sensing requires a ***fundamentally new approach to interferometric collection and processing***. The payload capacity of the smaller low-cost HALE platforms requires a radar instrument that is significantly lower weight and lower power than current SAR / InSAR instruments. Additionally, the relatively slow velocities and often irregular trajectories of high-altitude platforms cause traditional SAR/InSAR processing methods to break down.

Aloft Sensing, Inc. is developing a compact SAR / InSAR payload that satisfies the payload capacity of the smallest HALE class of vehicles, as well as the **innovative processing and positioning techniques** to address HALE-specific operational challenges, creating an STV-enabling system capability from the stratosphere.

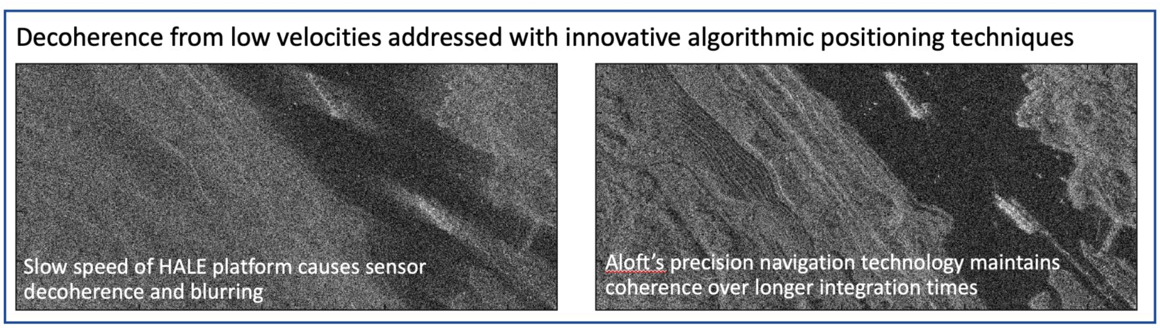
CHALLENGES OF SAR AND INSAR ON HALE, AND SOLUTIONS

Three principal challenges with operating synthetic aperture radar (SAR), interferometric SAR (InSAR), or multi-baseline distributed sensing from high-altitude long-endurance (HALE) platforms for STV applicability are:

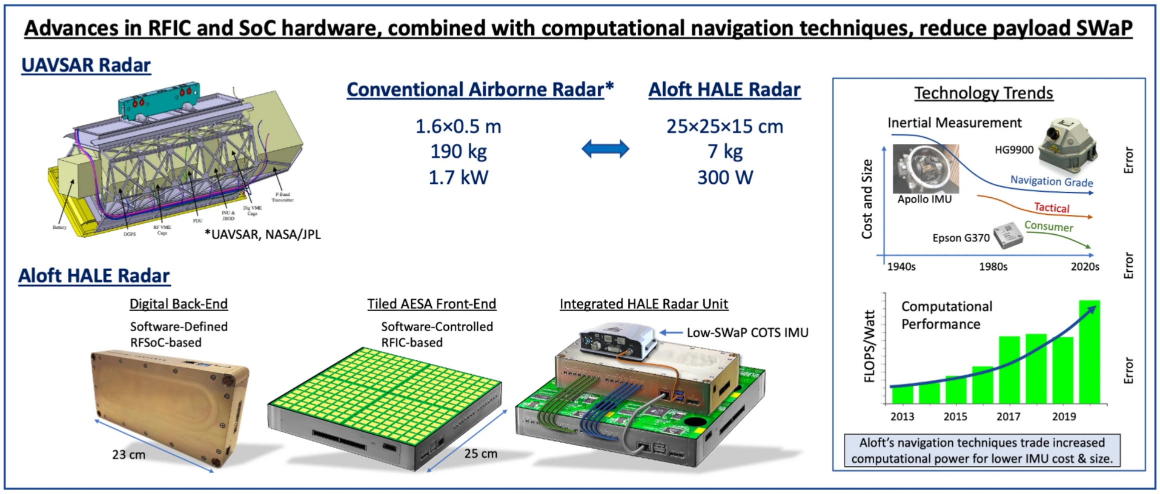
1. Slow velocity of HALE platforms creates long collection apertures (e.g., 10 minutes); typical track correction techniques will decohere over this interval.
2. The smaller HALE platform class is highly limited in payload size, weight, and power (SWaP) capacity; significant compaction and efficient integration is needed to achieve high-performance capabilities within a smaller package.
3. HALE navigation abilities are coarse, creating non-linear flight trajectories and making pass repeatability for InSAR difficult.
4. Distributed interferometric sensing techniques, such as polarimetric InSAR (PolInSAR) or tomographic SAR (TomoSAR), require ultra-precise relative positioning and timing knowledge in order to coherently combine the multi-baseline observations across the formation.

Aloft Sensing, Inc. (Aloft) is developing a HALE radar payload solution that solves the above challenges with a combination of innovative navigation techniques, optimized algorithms, system design, and by leveraging market hardware advances.

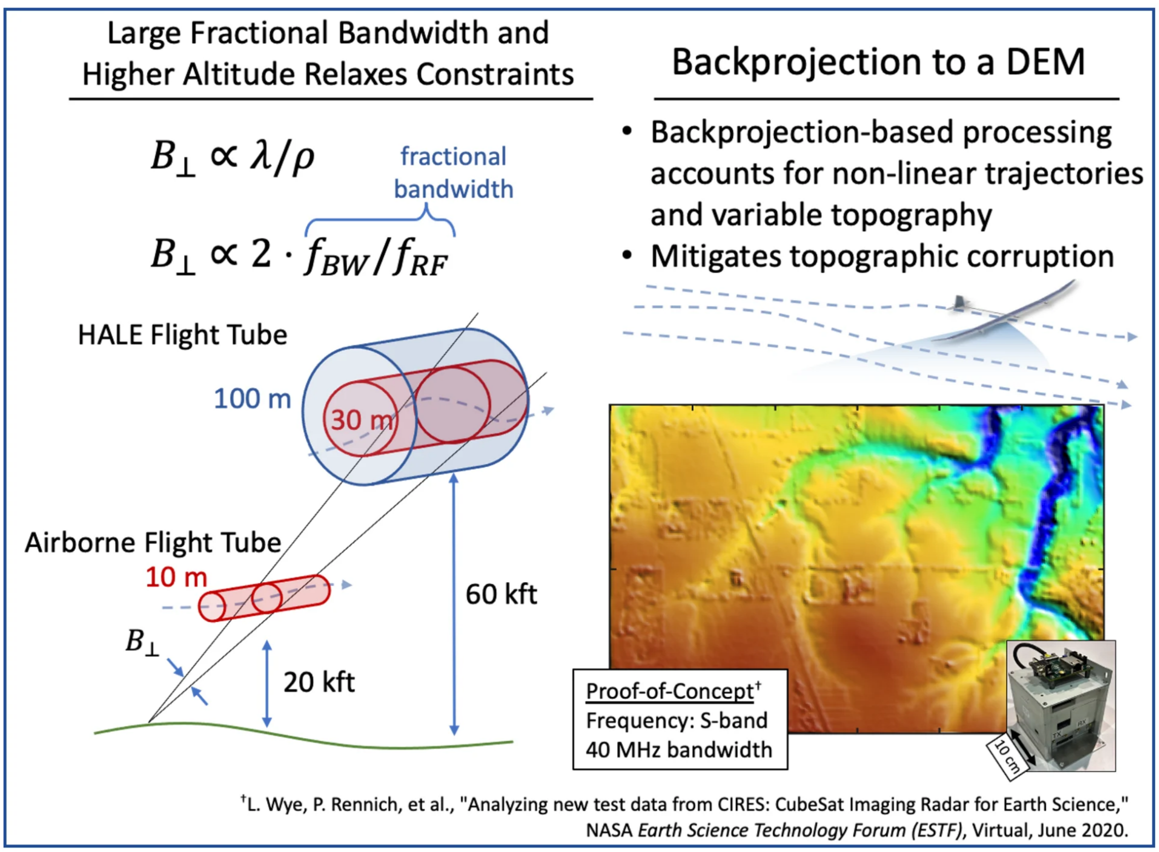
Slow Velocities and Decoherence: Aloft's patent-pending algorithmic high-precision navigation techniques (with positioning on the order of microns) provide the ability to maintain high coherence over long integration times, when traditional track correction techniques break down.



SWaP Constraints: Aloft's positioning techniques rely on computational processing and significantly relax the requirements on IMU support hardware, providing a path towards lower overall system size, weight, and cost. To further reduce SWaP, without compromising on performance, Aloft leverages advances in off-the-shelf radio-frequency integrated circuit (RFIC) and System-on-Chip (SoC) hardware technology to create a tightly-integrated, high-performance, and affordable payload solution.

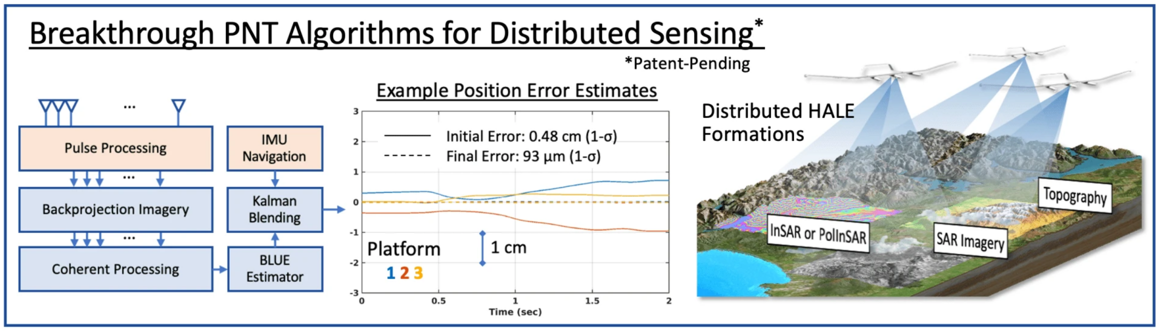


Limited Navigation Ability: HALE platform's coarse navigation control has a particular impact on repeat-pass InSAR applications, where flying outside of the critical baseline, or flight tube, causes coherence degradation and topographic corruption of noise. To overcome this limitation, Aloft's HALE radar payload maintains a large fractional bandwidth that, when combined with the higher stratospheric altitudes, relaxes the repeat-pass flight tube constraints. Aloft further uses backprojection-based processing to account for HALE non-linear trajectories and to mitigate topographic corruption of the interferometric phase.

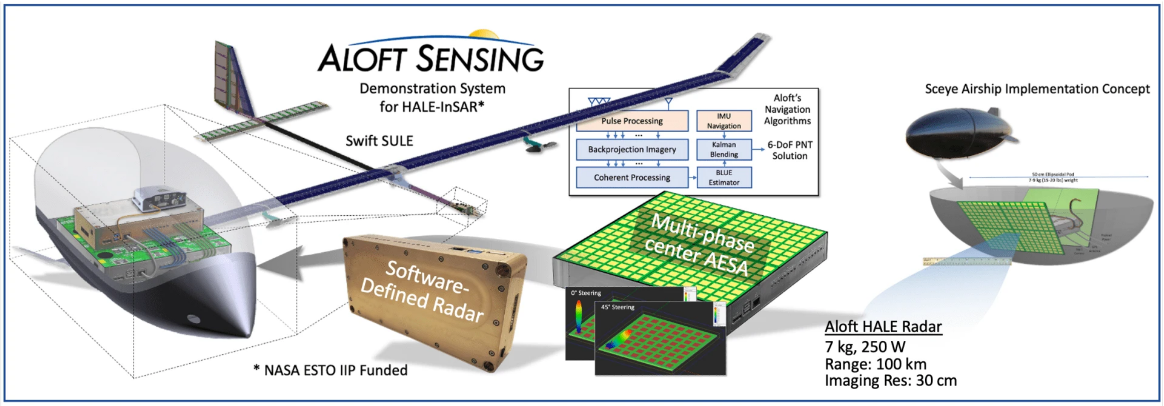


Distributed Formations and PNT: Techniques for collecting InSAR data over multiple simultaneous baselines are emerging as key enablers for new insights into STV science. To fully realize the accuracy and resolution benefits of these distributed interferometric techniques, however, the precise relative positioning and timing of the distributed sensing platforms must be known to a small fraction of the radar wavelength and the equivalent distance in time. Existing GNSS and differential-GNSS positioning approaches provide 3-5 cm accuracies and 20 ns relative timing, levels that are insufficient for establishing distributed coherence at S-band (10 cm wavelength) and above.

Aloft's patent-pending positioning, navigation, and timing (PNT) algorithms provide each radar sensor with the ***ultra-precise relative position and timing information*** required to effectively combine multi-baseline observations and form distributed interferometric products at the quality necessary for STV applicability. Aloft's PNT algorithms are capable of providing micron-level positioning, milli-degree orientation, and picosecond timing directly from the platform's radar waveforms, independent of GNSS coverage and requiring no ground support. Aloft has demonstrated the necessary levels of precision and accuracy, both theoretically and with representative field data.



ALOFT BREAKTHROUGH COMPACT RADAR SYSTEM FOR HALE



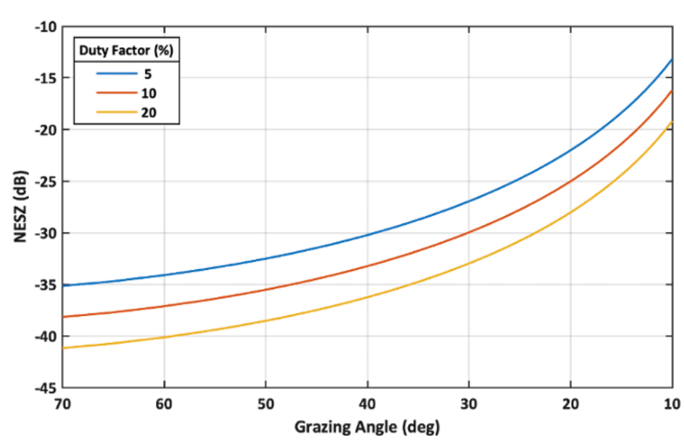
With NASA Earth Science Technology Office IIP funding, Aloft is developing and demonstrating a compact (7 kg; 25cm x 25cm x 15 cm) power-efficient (<300 W) X-band (9.6 GHz) radar payload that is compatible with the full range of HALE platform platforms, from Swift Engineering's nimble and light Swift Ultra Long Endurance (SULE) aircraft, to Sceye's large and capable airship. The complete system capability promises continual (e.g., sub-hourly) and precise collection of surface deformations, topographic changes, and volumetric measurements that are unattainable with any other existing method, providing a unique capability to fulfill key STV observables.

The Aloft payload, created with industry partners, leverages newly available RFSoC and front-end RFIC components to achieve a **breakthrough level of integration and power efficiency to meet the tightest SWaP constraints** imposed across the HALE platforms. The payload comprises a flexible software defined radar (SDRr), a lightweight and high-power active electronically steered antenna array (AESA), embedded onboard processing, and the **advanced algorithmic components** required to overcome the challenges of SAR/InSAR/Distributed operation from HALE (see Challenges section).

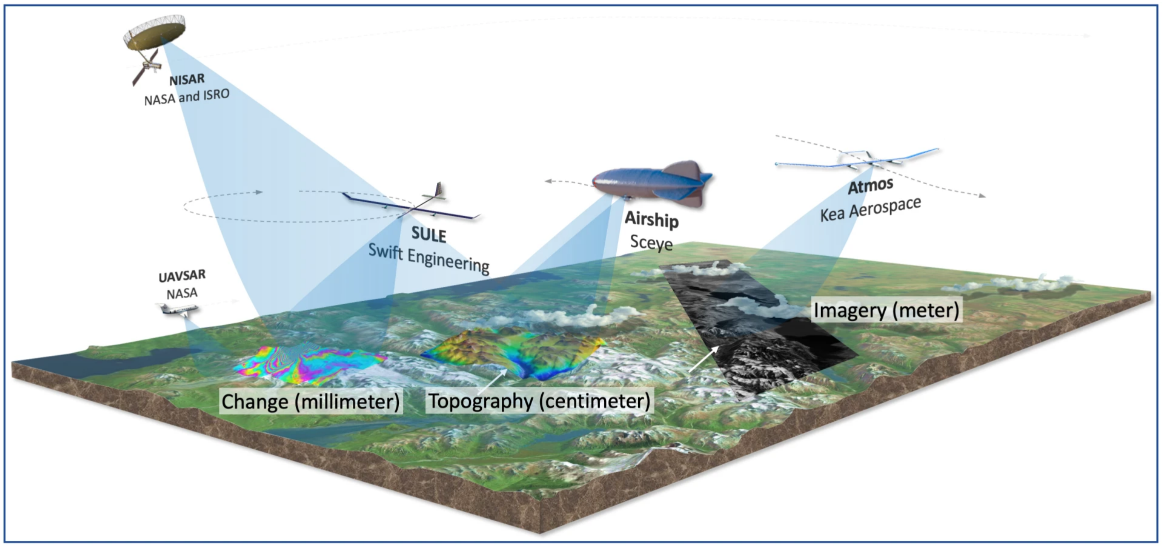
Predicted Instrument Performance from the Stratosphere. The key metric for establishing radar performance is noise-equivalent σ-zero (NESZ), a metric that represents the system noise level. To maximize interferometric coherence levels for typical solid surface types, NESZ smaller than -20 dB is desired. Using the instrument parameters in the table below, and modifying the waveform duty factor as needed, the resulting NESZ exceeds the desired threshold out to 10° grazing angles, or 100 km slant range, showing that the instrument-as-designed has the signal-to-noise sensitivity required to perform precise interferometric measurements.

Aloft HALE Radar System Parameters and Predicted Performance

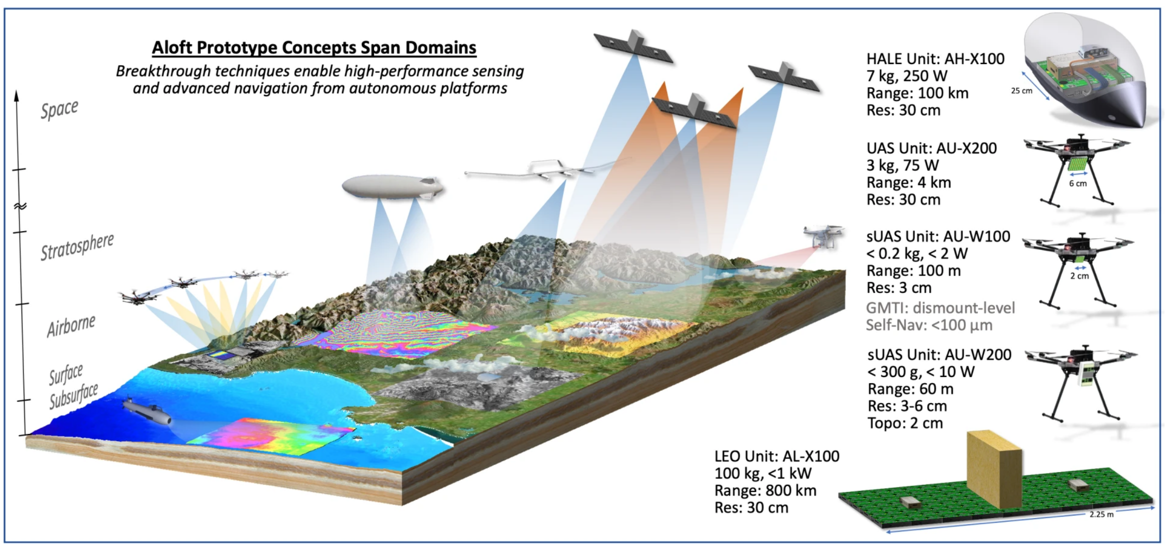
Parameter	Value
RF Tx Power (avg)	50 W
Tx Gain	23 dB
Rx Gain	23 dB
Wavelength	3 cm
Slant Range	30-100 km
Altitude	60 kft
System Losses	4 dB
System Temp	290 K
Noise Figure	3 dB
Platform velocity	8 m/s
Range Resolution	30 cm



The HALE-borne payload capability inserts readily into a ***larger Earth observing system*** to complement existing NASA orbital and airborne SAR/InSAR assets, enabling coordinated multi-frequency differential measurements for broad-area, synoptic comparisons.



The payload is further designed to **support distributed formation and mesh sensing operations** and is scalable across the domains, from low-altitude to space. Aloft is currently testing a prototype version of the payload on low-altitude UAS under an Army RCCTO Direct-to-Phase II SBIR effort.



STV-RELEVANT PERFORMANCE

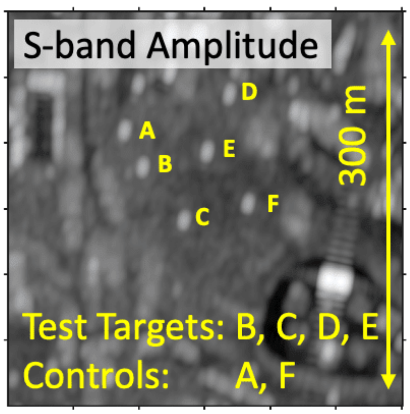
Surface Topography and Vegetation (STV) science investigations require **precise measurements of surface changes, topographic heights, and volumetric reconstructions**. To demonstrate the capabilities of Aloft's algorithms to achieve the necessary precision and accuracy, we have applied our techniques to publicly available field data collected from the ESTO-funded CubeSat Imaging Radar for Earth Science (CIRES) by the Aloft team under prior employment. Airborne data collected with this compact radar system from repeat- and cross-track passes exhibit properties similar to what will be experienced from high-altitude stratospheric systems and face similar processing challenges.

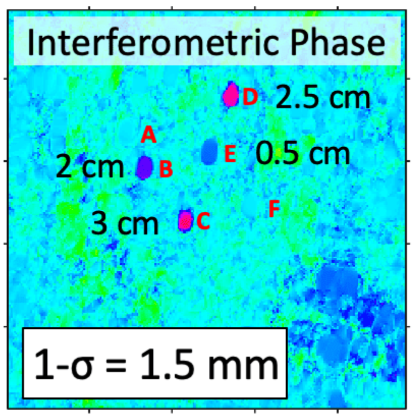
Aloft processed the CIRES field data to demonstrate two key capabilities relevant to STV:

1. Detection of millimetric surface changes, and
2. Reconstruction of centimetric topographic heights

The CIRES system observed trihedral reflectors that were adjusted by heights of 5, 10, and 30 mm between passes. Aloft processed the data employing our patent-pending positioning techniques to establish the precise interferometric baseline between the nominally repeat-track passes. The motion measurements extracted from the resulting interferograms demonstrate that the algorithms achieve deformation accuracies better than ±1.5 mm for repeat-track airborne InSAR. These same techniques are directly applicable to collections obtained from stratospheric platforms.

Millimetric Change Detection Enabled by Aloft Positioning Techniques (Example uses CIRES field data)

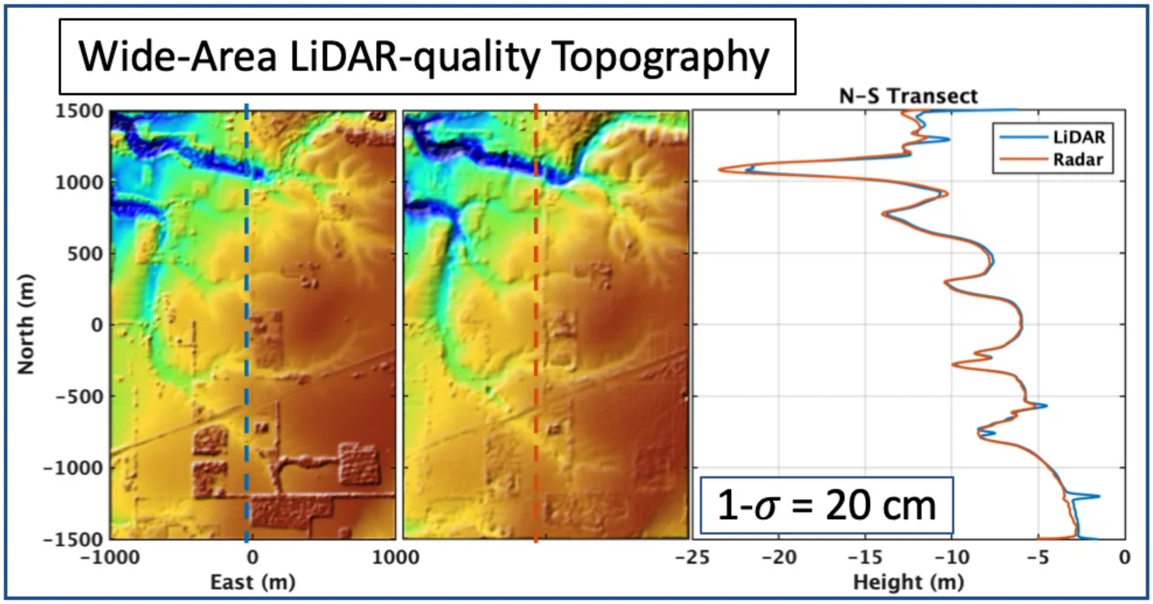




Targets	Mean Error (μ)	Std Error (1-σ)
A	0.0 mm	0.6 mm
B	2.6 mm	2.2 mm
C	-2.3 mm	1.6 mm
D	-1.5 mm	2.0 mm
E	0.0 mm	0.6 mm
F	-0.7 mm	1.1 mm

† L. Wye, P. Rennich, et al., "Analyzing new test data from CIRES: CubeSat Imaging Radar for Earth Science," NASA *Earth Science Technology Forum (ESTF)*, Virtual, June 2020.

Aloft also applied their algorithms to measure terrain height from cross-track CIRES collections. After application of the Aloft techniques, the topography extracted from cross-track interferograms compared favorably to LiDAR data collected over the same area. Analysis shows that a height accuracy of 20 cm (1-σ) is achieved. The reconstruction of ***centimetric terrain heights*** is accomplished over the wide-area radar swath without reliance upon in-scene fiducials, which is important to maximize general science applicability.



These demonstrations with field data, along with others conducted by Aloft at different radar frequencies, show the applicability and utility of our techniques for high-accuracy HALE-based surface deformation and topographic investigations.

To address the STV need for **3-D volumetric reconstructions** of surface vegetation and other structures, Aloft has developed a set of patent-pending PNT algorithms that are capable of providing the micron-level positioning, milli-degree orientation, and picosecond timing accuracy necessary for precise multi-baseline distributed interferometric measurements (see Challenges section for additional details). Future work will support embedding the Aloft PNT techniques within radar sensors carried by HALE (and other vehicles), enabling the precise real-time platform positioning and timing information necessary to achieve full coherence over the constructed multi-baseline apertures and realize the enhanced vertical accuracy, resolution, and latency requirements required for STV science (e.g., 3 cm vertical accuracy, 0.5 m vertical and 1 m horizontal resolution, and 0.5 days latency).

AUTHOR INFORMATION

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