THE EXPERIMENT FOR CRYOGENIC LARGE-APERTURE INTENSITY MAPPING (EXCLAIM)

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I: ABSTRACT

The EXperiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM) is a **high-altitude balloon telescope** designed to deepen our understanding of star formation in a cosmological context, shedding light on why the star formation rate declines and breaks away from the cosmological evolution of dark matter for redshifts z>2 [1].

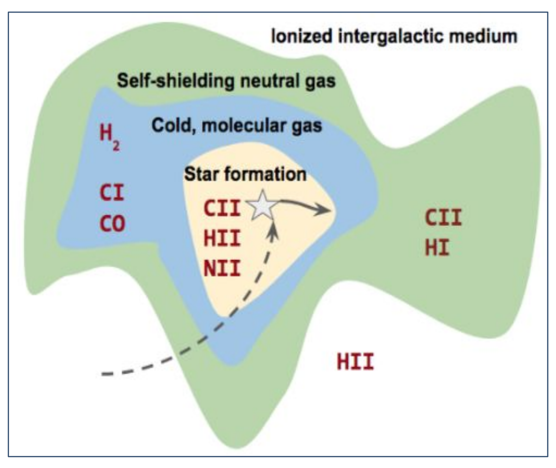
EXCLAIM will operate at 420–540 GHz with a spectral resolution of R=512 to measure the integrated line emission from galaxies and the intergalactic medium (IGM), in particular CO and [CII] line emissions from the nearby universe out to redshifts of z~3.5. This approach is known as **Intensity Mapping** (IM), which provides efficient access to large cosmological volumes and redshifts with sensitivity limited by detector noise or photon background, while requiring modest apertures.

The instrument will employ an array of **six superconducting integrated grating-analog spectrometers** (μ-Spec) with superconducting microwave kinetic inductance detectors (KIDs) in an all-cryogenic telescope (1.7 K) to achieve near background-limited sensitivity.

Here, we present an overview of the EXCLAIM instrument and status, with emphasis on the Attitude Determination & Control System (**ADCS**) and the **thermal** system.

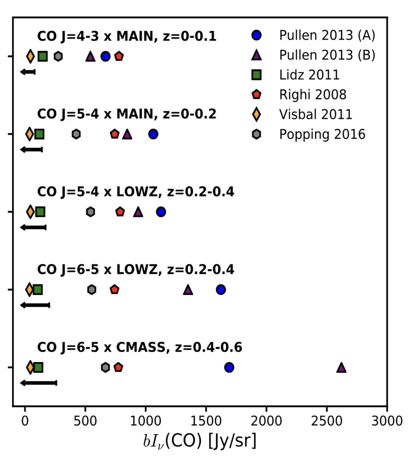
II: SCIENCE

EXCLAIM will map the sub-mm emission of redshifted carbon monoxide (CO) as well as singly-ionized carbon ([CII]) lines over redshifts 0 < z < 3.5, and will also map [CI] lines produced in photodissociation regions (PDRs) in the Milky Way. These line emissions are key tracers of the gas phases in the interstellar medium involved in star-formation processes, but have only preliminary characterization beyond the nearby universe.



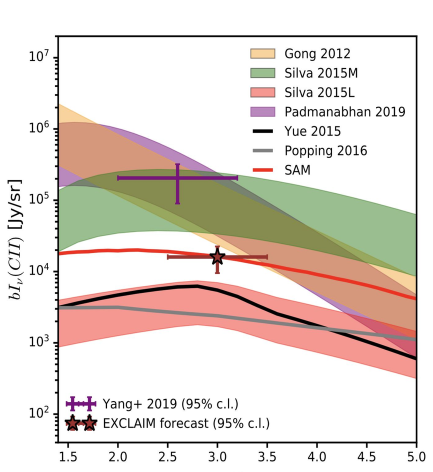
Primary Science Questions:
1. What factors led to the dramatic decline in star formation after z ~ 2 in contrast to dark matter evolution?
2. What is the typical abundance, excitation and evolution of the molecular gas which forms stars?
3. How well does CO trace H_2 in galaxies?
4. Is intensity mapping a viable approach to probe high redshifts?

CO: EXCLAIM will cross-correlate with spectroscopic galaxy redshift catalogs to constrain the total CO line brightness from 0 < z < 0.7 and potentially out to z = 1 with extended BOSS survey releases. This traces the abundance of gas available to form stars.



CO total brightness for several J ladder lines, with EXCLAIM sensitivity (black line) compared to existing models [2-6]. Here, J is the transition, *b* is the clustering bias of the emitters and I_v is the intensity.

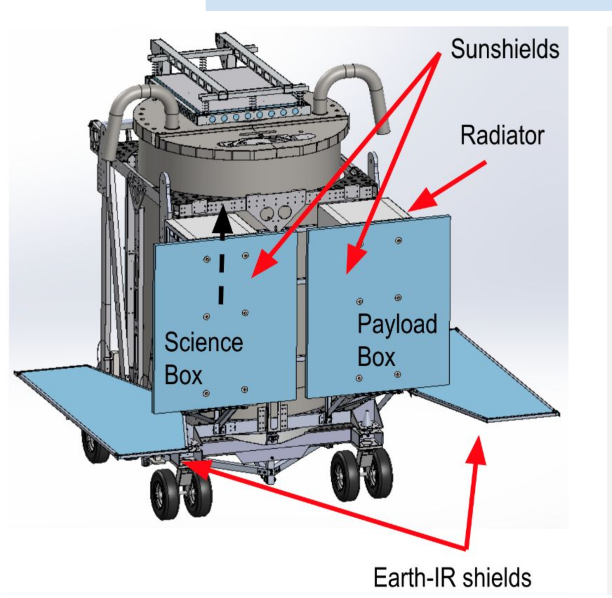
CII: EXCLAIM will cross-correlate with the BOSS QSO survey from 2.5 < z < 3.5 to provide a definitive test of CII brightness (shown right) and probe the CII and the star formation rate (SFR) relation [8], determining whether it follows local relations or suggests strong evolution of the average interstellar medium.



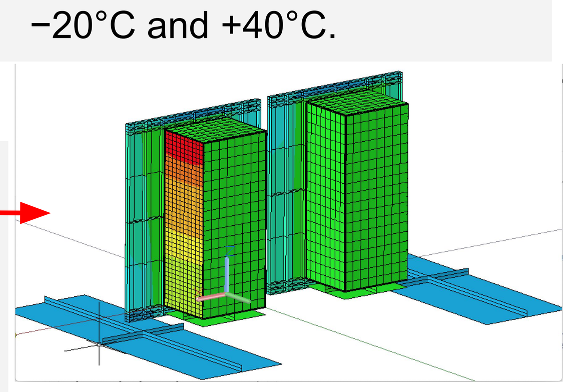
CII total brightness as a function of redshift. EXCLAIM sensitivity (red star) is compared to existing models [3,9-11] and preliminary measurements [7]. Here, *b* is the clustering bias of the emitters and I_v is the intensity.

CI: EXCLAIM will map neutral carbon emission in the Milky Way, providing data to determine the co-extensiveness of [CI] and CO gas in galactic photodissociation regions (PDRs), and probe existing assumptions about the [CI]/CO intensity ratios.

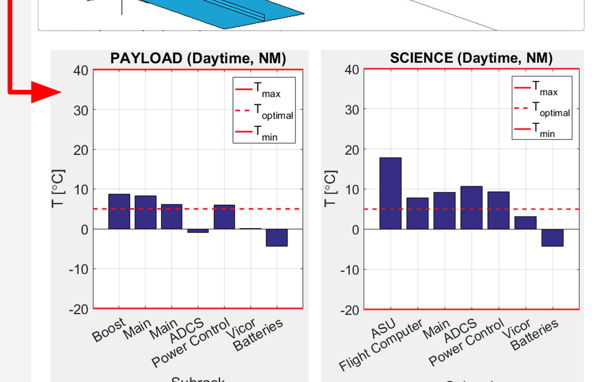
III: THERMAL DESIGN



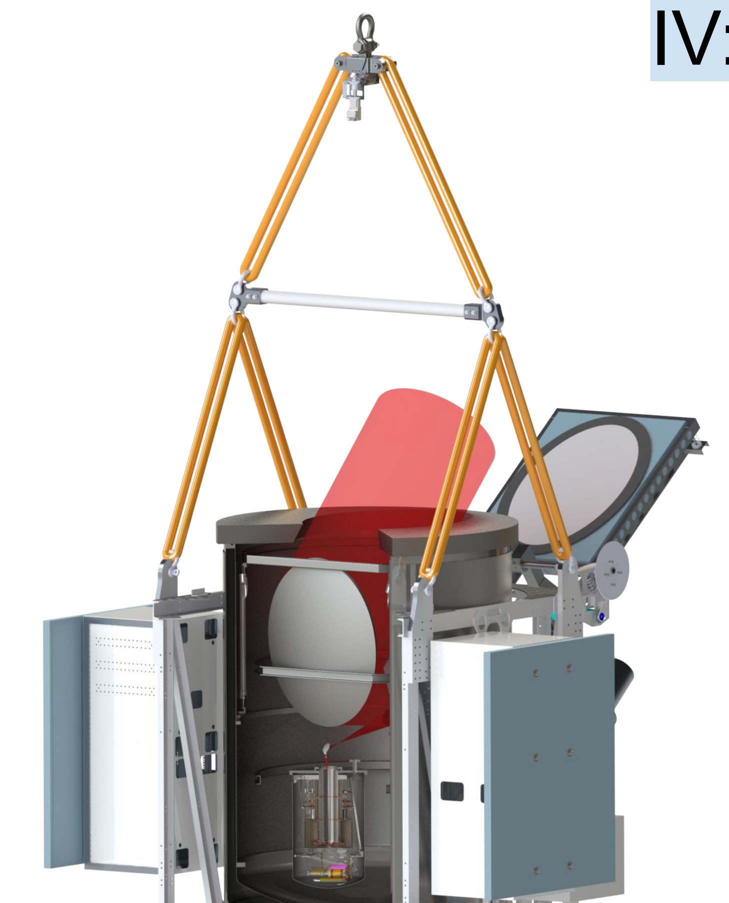
- The gondola thermal design must account for:
  - **ascent** (rapid cooling)
  - **daytime float** (solar direct and albedo loading)
  - **nighttime float** (radiative cooling and Earth IR loading)
- **REQUIREMENTS:** Electronics and batteries must be maintained between −20°C and +40°C.



- **High-fidelity model**: Thermal Desktop
- **Low-fidelity models**: Veritrek (upcoming), MATLAB
- Thermal simulations bracket a hot and cold case for operations.
- With conservative estimates of the payload power use, we find that **temperatures are maintained within operating ranges** and require heaters in ascent and nighttime float.



IV: INSTRUMENT OVERVIEW



Cryogenic Balloon-Borne Instrument:
- **29-37 km altitude** at float on either an 11 or 34 million-cubic-foot (MCF) balloon.
- 3500 liters of liquid helium gives **~24 hrs of operation** at 1.7 K at float altitude.
- Adiabatic Demagnetization Refrigerator cools the detectors to 100 mK from the 4.3 K (ground) to 1.7 K (float) helium bath temperature.
- Superfluid He pumps distribute the liquid He to cool the optics.
- **μ-Spec** integrates all the elements of a grating spectrometer - the dispersive element, filters, and detectors - **on a single chip [11,12]**.
  - Phase delay is introduced by a synthetic grating made of superconducting Nb microstrip lines patterned on both sides of a single-crystal Si substrate [13]. The high index of refraction of Si shrinks the spectrometers, allowing 6 to fit on a 6" wafer. A 2D parallel plate waveguide region in a Rowland circle architecture serves as a spatial beam combiner and focal plane [14]. An order-choosing filter selects the design order.
- **Heritage:**
  - From **PIPER** (Primordial Inflation Polarization ExploreR) [15]: gondola, housekeeping electronics, software and ADR designs.
  - From **BLAST-TNG** (Balloon-borne Large-Aperture Submillimeter Telescope - The Next Generation) [16]: MKID readout.

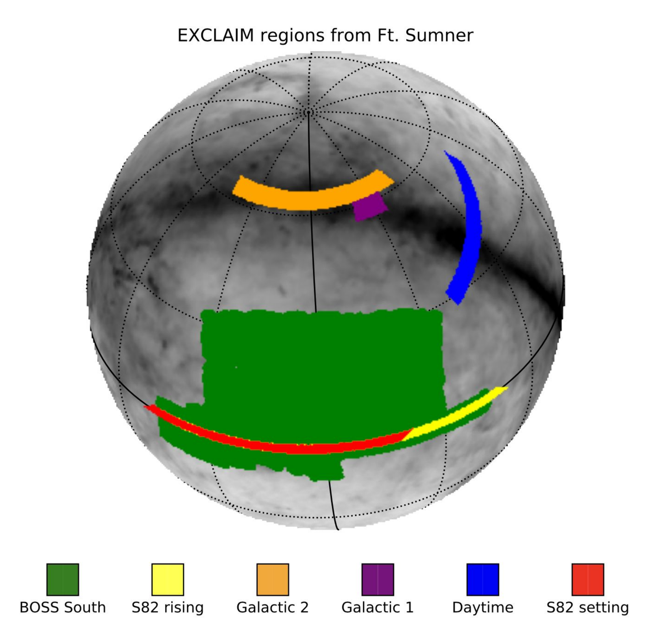
EXCLAIM Instrument & Telescope Parameters

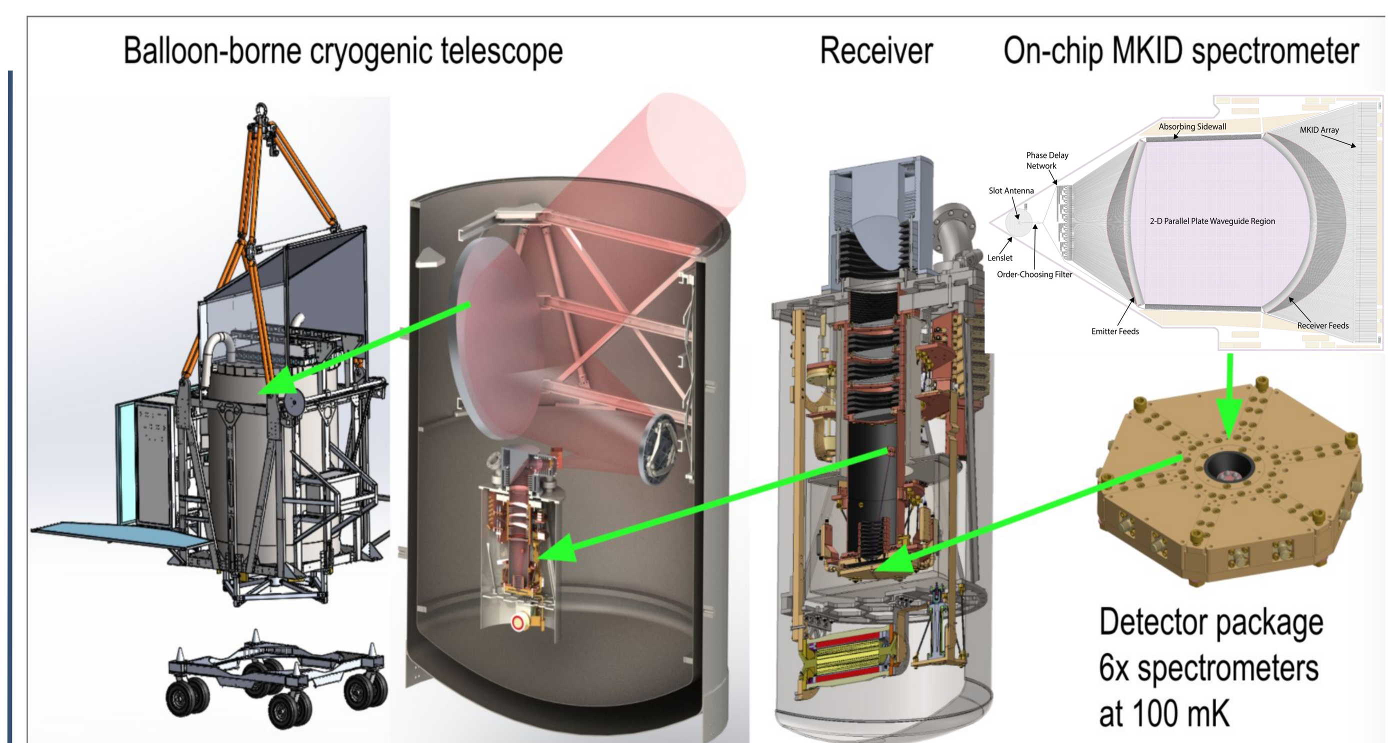
Mass	3200 kg
Height	2.8 m
Telemetry rate	57.6 kpbs
Data rate	9 MB/s
Gondola power	1500 W
Projected aperture	74 cm
Angular resolution	4.3' FWHM
Telescope f/#	1.3
Detector spacing	2.2 f λ
Instantaneous FOV	12.5'

EXCLAIM Spectrometer & MKID Parameters

Spectrometer design	μ-Spec, antenna-coupled diffraction-grating analog, Rowland configuration
Number of spectrometers	6
Spectral range	420–540 GHz
Spectrometer grating order	2 (operates over a single order)
Resolving power, R = λ/Δλ	512 at 472 GHz (central frequency), 535-505 over the spectral band
Spectrometer efficiency	~23% (from Si lens input to the MKIDs)
Spectrometer materials	Nb planar transmission line, single-crystal Si dielectric
MKIDs per spectrometer	355
MKID materials	20-nm-thick Al microstrip, single-crystal Si dielectric, ground plane Nb
MKID readout band	3.25–3.75 GHz
Detector NEP	8 x 10^{-19} W/√Hz under typical loading (0.16 fW absorbed at KID)
Operating temperature	100 mK

V: INSTRUMENT & OBSERVING STRATEGY



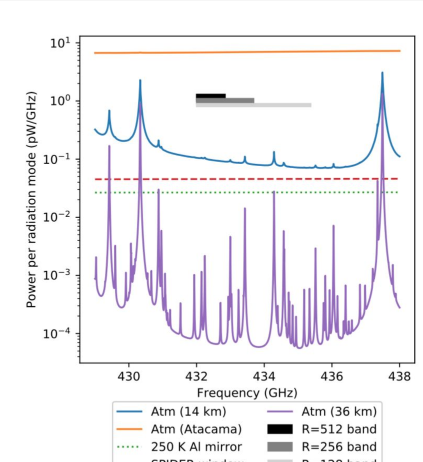


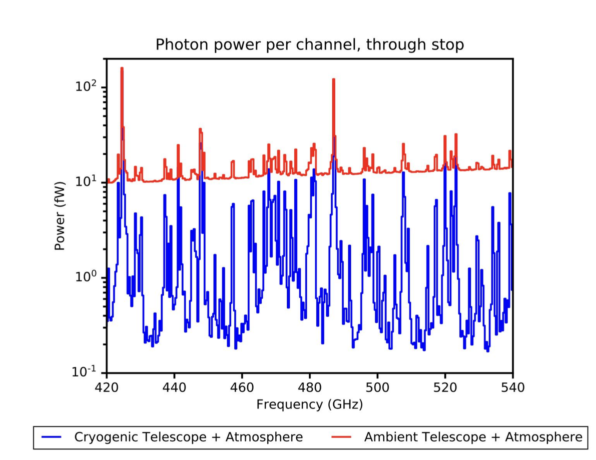
We **cross-correlate with** the Baryon Oscillation Spectroscopic Survey (**BOSS**) Stripe 82 for primary science – a reference survey is shown above. Cross-correlation can go wide to access from linear scales up to k~1 *h*Mpc^{-1}. Several Milky Way regions will map [CI].

Plan for a conventional **flight from Texas or New Mexico**, as it is well matched to surveys of the BOSS-North/South region, and has simple logistics, high recovery rate, and frequent flight opportunities.

The telescope is an off-axis Gregorian configuration with 90-cm parabolic primary mirror, a 10-cm folding flat and a parabolic secondary mirror, all machined of aluminum. The f/1.5 reflectors feed a single Si lens through a stop. A lenslet feeds a slot antenna on the on-chip spectrometers. The stop controls illumination of the primary and terminates stray light onto blackened cold baffles. The receiver must remain superfluid-tight, so uses indium seals to form a "submarine" with a silicon window [17].

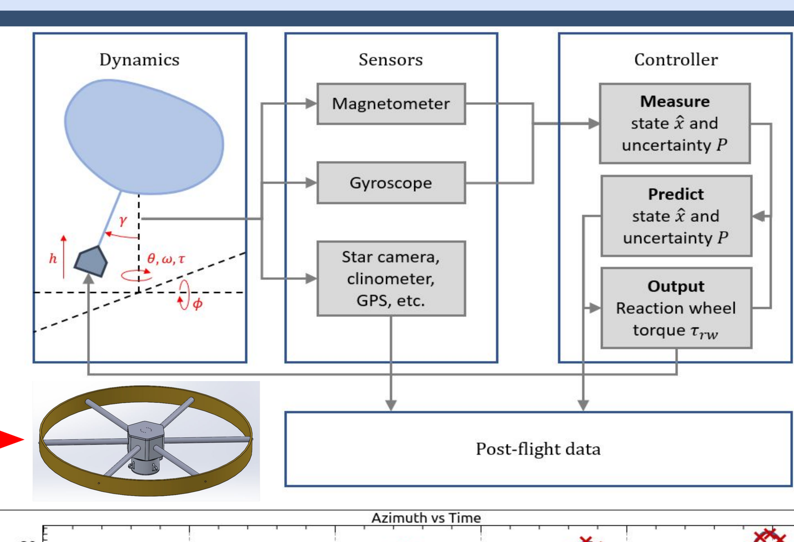
Why Cryogenic? In EXCLAIM's wavelengths, the atmosphere and objects at ambient temperature are much brighter than the cosmological signal. At balloon flight, the atmospheric column depth drops dramatically. Additionally, the atomic and molecular lines narrow because of lower pressure broadening. This opens very dark windows with space-like sensitivity. To take advantage of these windows, an instrument needs spectral resolving power R>100 and cryogenic optics.

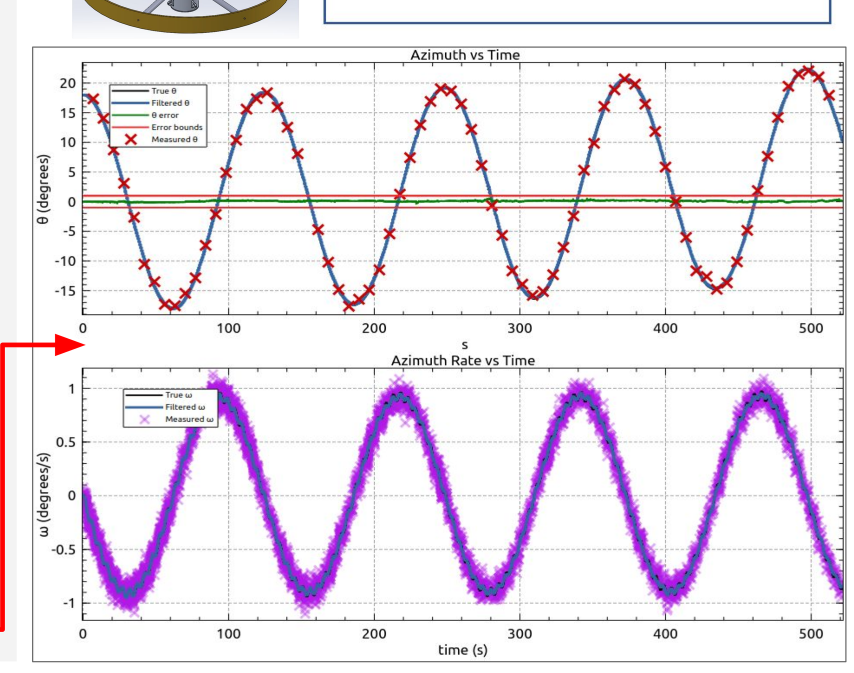




VI: ADCS DESIGN

- **Survey strategy:** sinusoidal azimuthal scan to survey rising and setting fields at a fixed elevation of 45°.
- **Execution:**
  - A **reaction wheel** (moment of inertia: 30 kg·m^2, total mass: 75.8 kg) executes the azimuth scan.
  - **Momentum dumping to the balloon through a rotator** to maintain the reaction motor speed below its saturation due to back electromotive force (EMF).
  - Peak torque (35 N·m) and angular rate (144°/s on the reaction wheel) to execute the scan require <50 W power (80% efficiency assumed).
  - Kollmorgen D063 brushless direct-drive DC motors drive the reaction wheel and rotator. The direct drive simplifies design and operation, eliminates backlash and reduces vibration.
- **Pointing:**
  - **Offline** pointing (for map production) must have noise <2% (5") of the optical FWHM to control jitter's impact on the effective angular resolution.
    - Based on **star camera** measurements acquired at the scan turnarounds and tied together by **gyroscope** data, using a **clinometer** to establish tilts.
  - **Online** pointing (for target survey) must be sufficient to establish the field center (<1°) and control the scan speed and total throw to maintain target fields.
    - **Kalman filter** and control system use gyroscope and **magnetometer** sensors to refine velocity and position, respectively, as shown here for free oscillation of the gondola on the flight train.





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CURRENT STATUS

The EXCLAIM program began in April 2019 and is in **Phase C** (final design and fabrication) of its life cycle, with system design approaching completion. An engineering flight is expected in 2022 and a science flight in 2023.