Sub-Arcsecond Performance of the ST5000 Star Tracker on a Balloon-Borne Platform

Eliot F. Young
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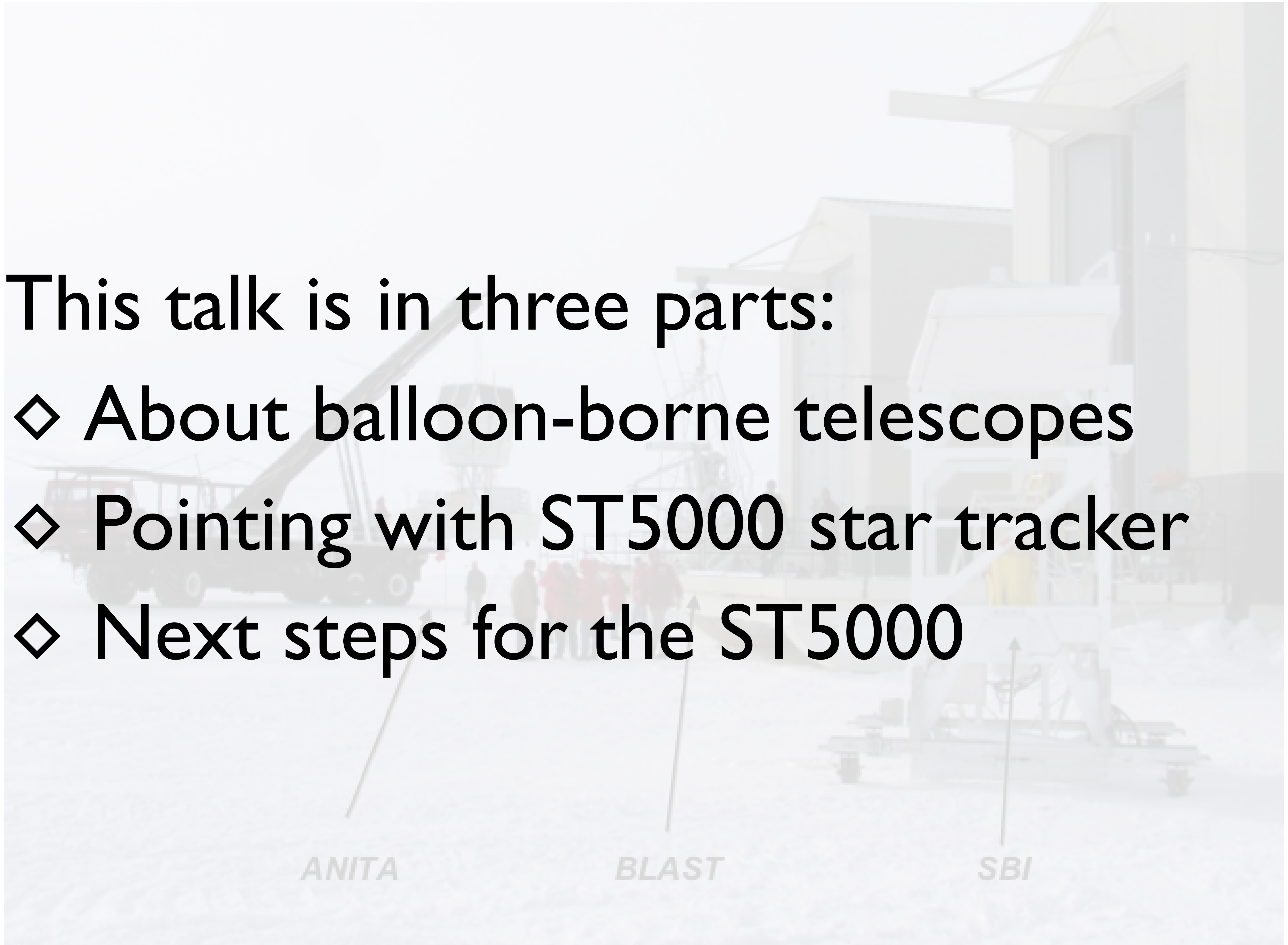
This talk is in three parts:

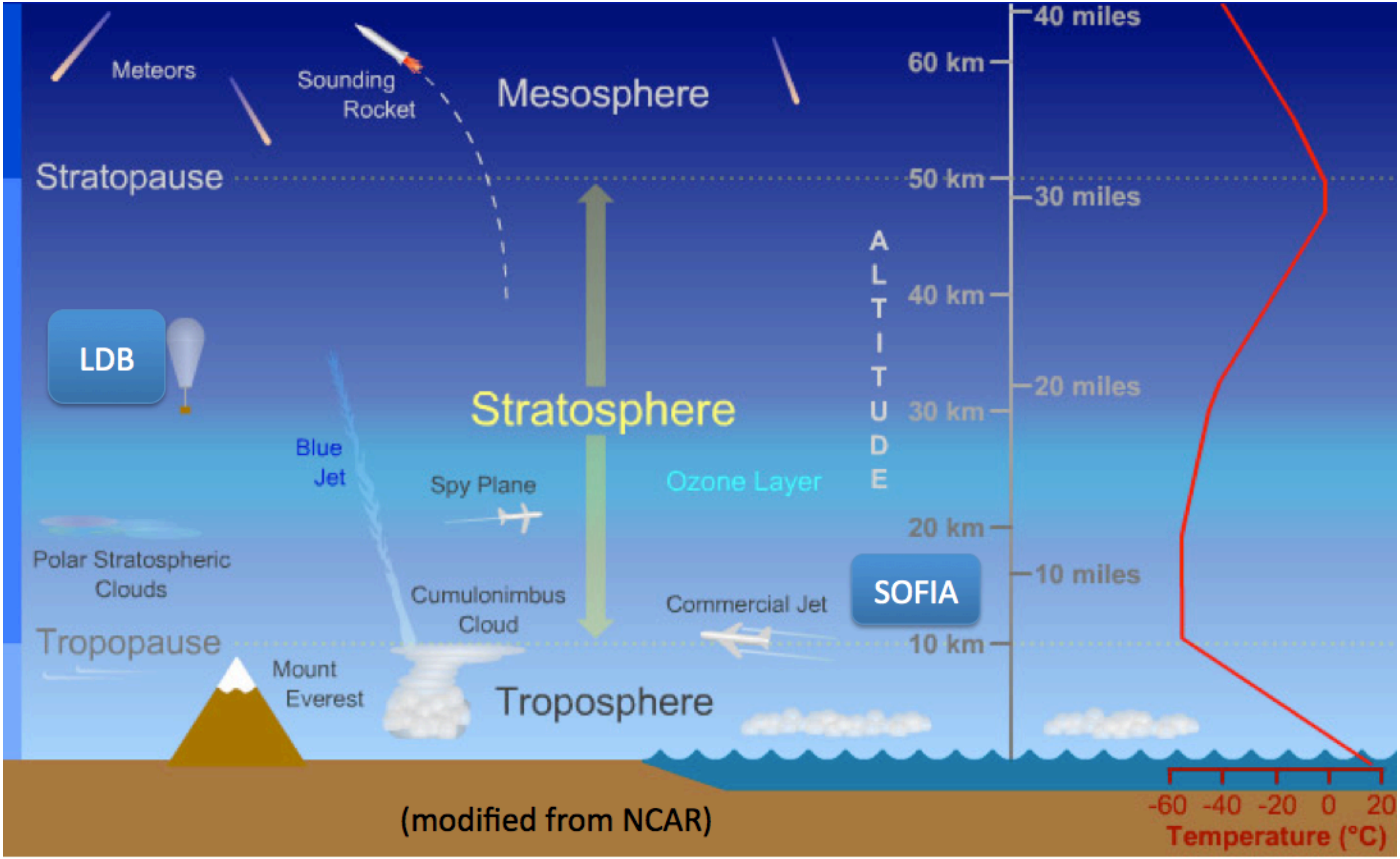
◇ About balloon-borne telescopes

◇ Pointing with ST5000 star tracker

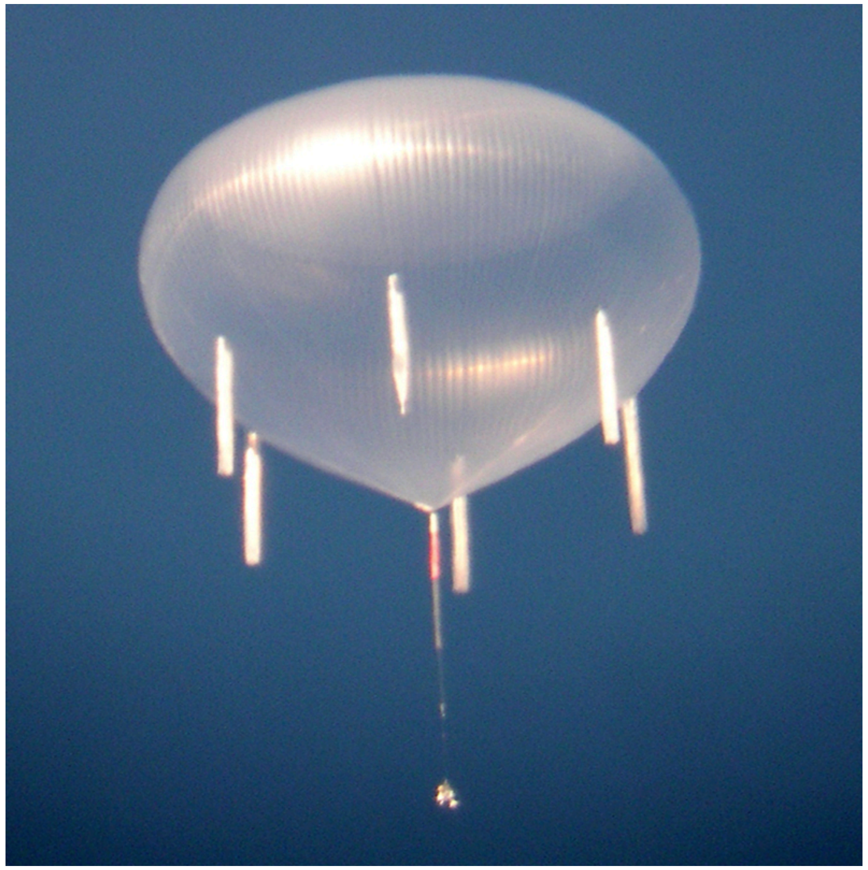
◇ Next steps for the ST5000



PART ONE: NASA's Balloon Program

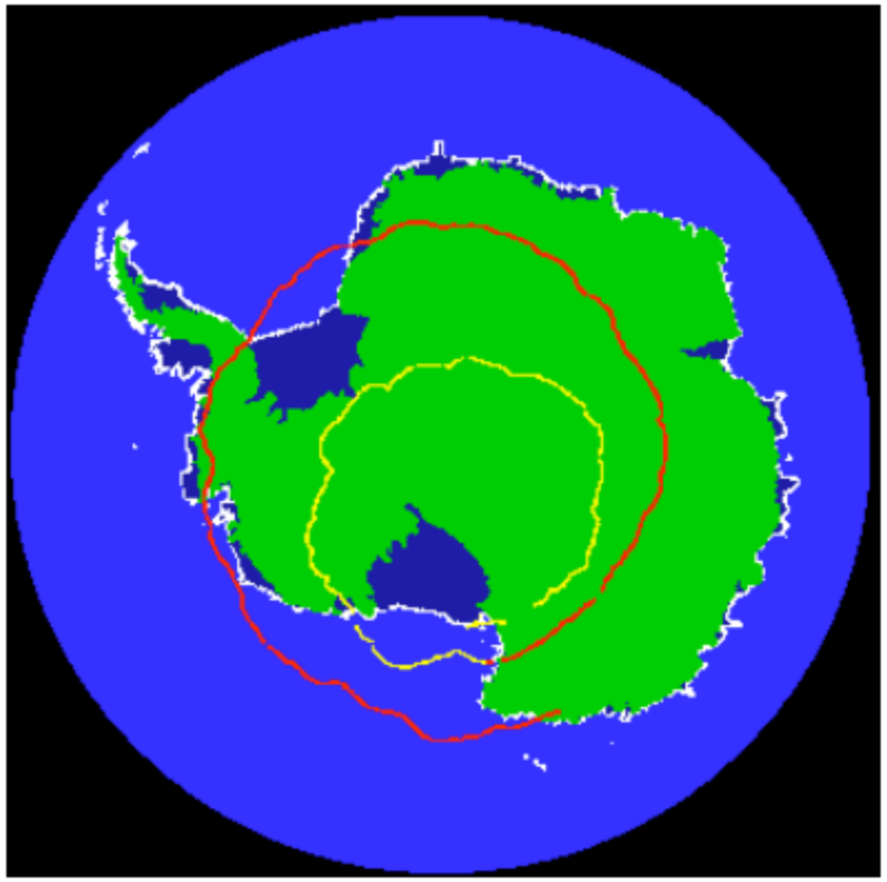


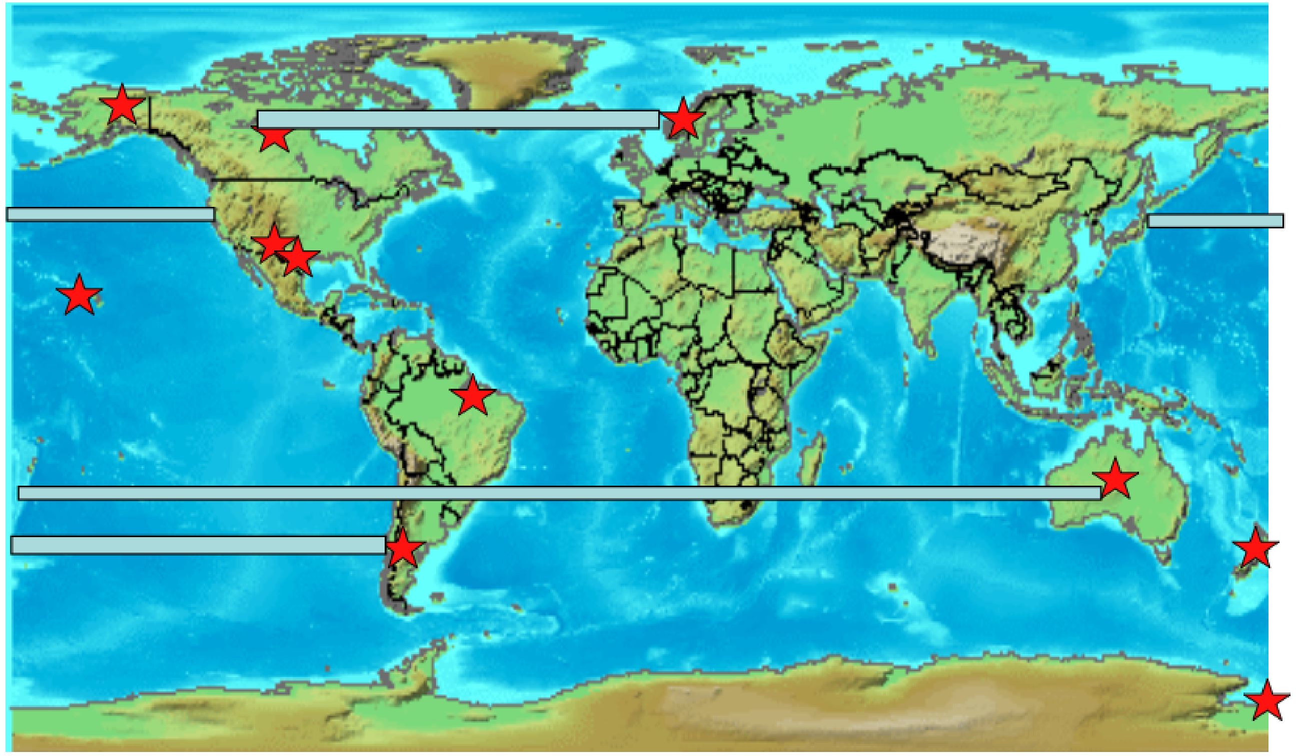
NASA's Balloon Program: Overview



- BPO flies payloads recommended (& funded) by NASA programs like APRA.
- Zero-pressure balloons, up to 8000 lb payloads, daily 10% vent/ballast cycles.
- Durations: 3-4 weeks from Antarctica.
- Altitudes:120,000 ft, above 99.5% of the atm.
- Worldwide launches (e.g., from Palestine, Ft Sumner, Kiruna, Alice Springs and Antarctica).

CREAM Trajectory, 19 Days 2009

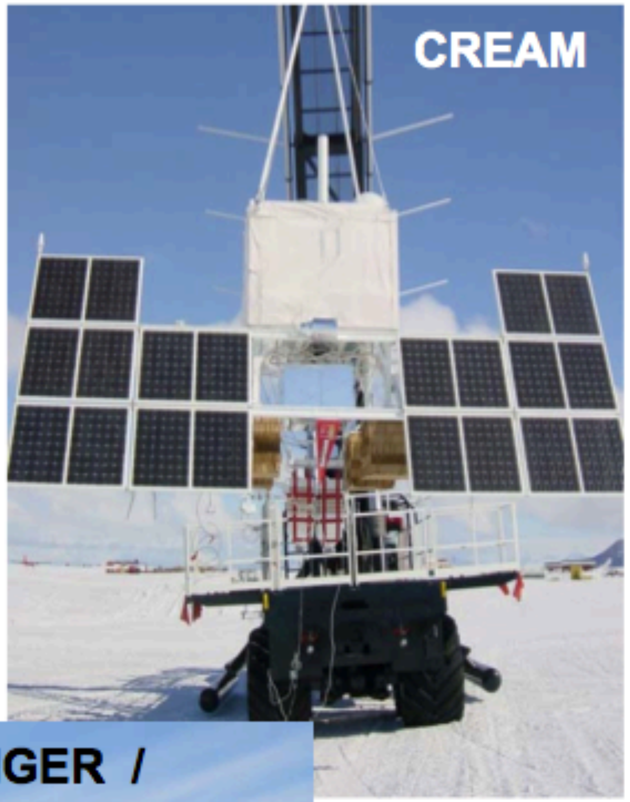




NASA's Balloon Program: Overview

	Conventional	LDB	ULDB*
Duration	~ 2 days	40+ days	Up to 100 days
Flight Opportunities	~16 per year	3-6 per year	1 per year
Suspended Capacity	1650-8000 lbs		6000 lbs
Float Altitude	Up to 160,000 ft		Up to 110,000 ft
Flight Support Systems **All NASA Flight Support Systems are highly reliable proven systems**	CIP •Line of Sight •300 kbps direct return	SIP •Over the Horizon •100 kbps TDRSS downlink	CDM/SIP •Over the Horizon •100 kbps TDRSS downlink
Launch Locations	Fort Sumner, NM; Palestine, Texas; Alice Springs, Australia	Antarctica; Kiruna, Sweden; Alice Springs, Australia;	
Operations Costs per flight, excluding Instrument	**ROM $ 100-250 K**	**ROM $ 250- 500 K**	**ROM $ 500- 1000 K**

NASA’s Balloon Program: Overview



NASA's Balloon Program: Overview

Balloon Size	*Maximum Suspended Weight (lbs)*	*Float Altitude (ft)*
59.84 MCF	1650	160,000
36.73 MCF	8000	120,000
39.97 MCF	6000	127,000
28.47 MCF	6500	119,000
11.82 MCF	7450	98,000
11.82 MCF	2875	116,000
4.0 MCF	3500	96,000

NASA's Balloon Program: Overview

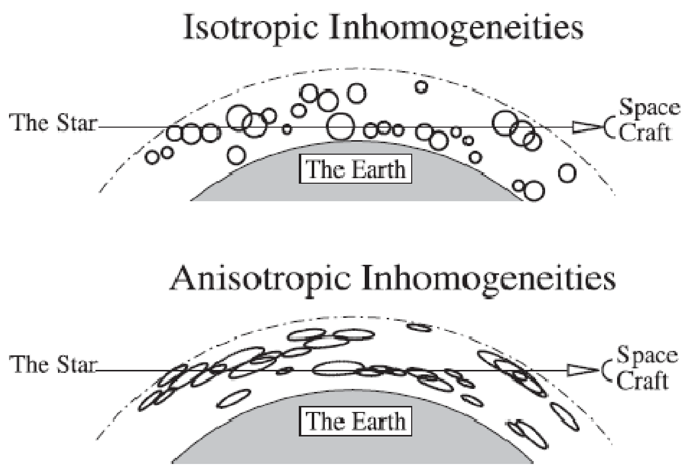
QUESTION: What is the environment like in the stratosphere at 120,000 ft (35 km)?

Specifically:
- How good is the seeing?
- How stable is the photometry?
- What is the telluric spectrum from 120,000 ft?
- What is the infrared background?
- What is the daytime background?

Question: What is the atmospheric seeing at 120,000 ft?

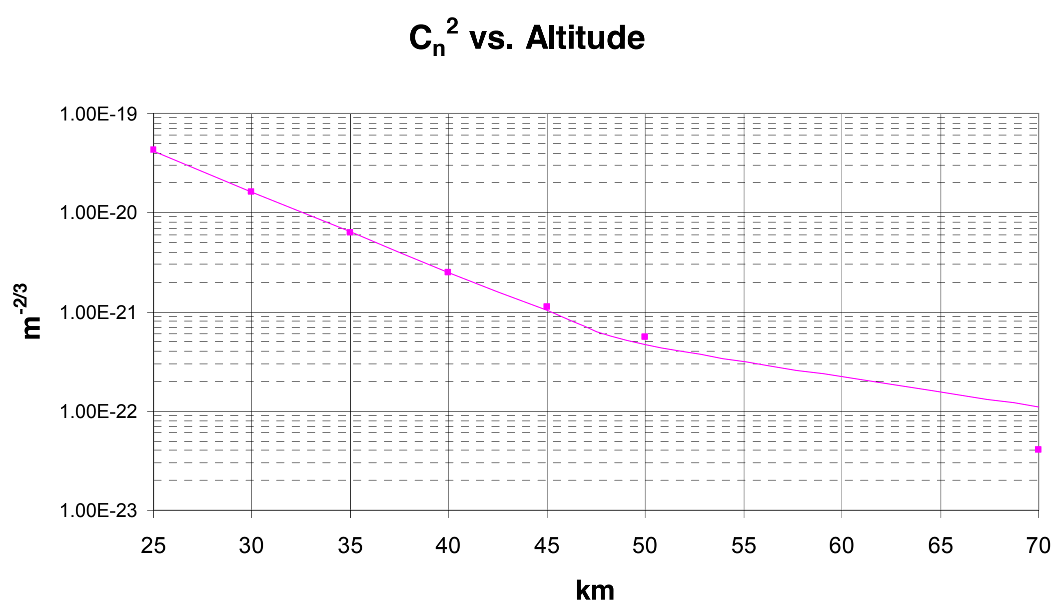
Natural Seeing

A Critical Feasibility Question: Will speckles generated by aberrations of free-atmospheric origin permit 10^{-9} contrast limit, assuming a perfect coronagraph?



Gurvich & Chunchuzov (2003) *JGR*, Gurvich & Brekhovskikh (2001) *Waves in Radom Media*

Seeing parameter	Balloon-borne (35 km alt.)	Ground-based
Fried r_0	41 m	0.2 m
Inner scale l_0	**2.4 m**	0.006 m
Outer scale Λ_0	44 m	27 m



Pin Chen, et al.

From a presentation by Pin Chen et al. 2009, KISS workshop on Innovative Approaches to Exoplanet Spectra.
< http://www.kiss.caltech.edu/workshops/exoplanet2009/>

Question: What is the atmospheric seeing at 120,000 ft?

Consider the SUNRISE mission, which launched from Kiruna (Sweden) in 2009.

During its 7-day mission it acquired tracked its target (the Sun) with rms errors of a few tens of milli-arcseconds.

It acquired the sharpest images to date of the Sun.

The SUNRISE Mission's Shack-Hartmann Experiment

Solar Phys (2011) 268: 103–123
DOI 10.1007/s11207-010-9676-3

THE SUNRISE BALLOON-BORNE OBSERVATORY

The Wave-Front Correction System for the *Sunrise* Balloon-Borne Solar Observatory

T. Berkefeld · W. Schmidt · D. Soltau · A. Bell · H.P. Doerr · B. Feger · R. Friedlein · K. Gerber · F. Heidecke · T. Kentischer · O. v. d. Lühe · M. Sigwarth · E. Wälde · P. Barthol · W. Deutsch · A. Gandorfer · D. Germerott · B. Grauf · R. Meller · A. Álvarez-Herrero · M. Knölker · V. Martínez Pillet · S.K. Solanki · A.M. Title

Received: 8 June 2010 / Accepted: 4 November 2010 / Published online: 8 December 2010

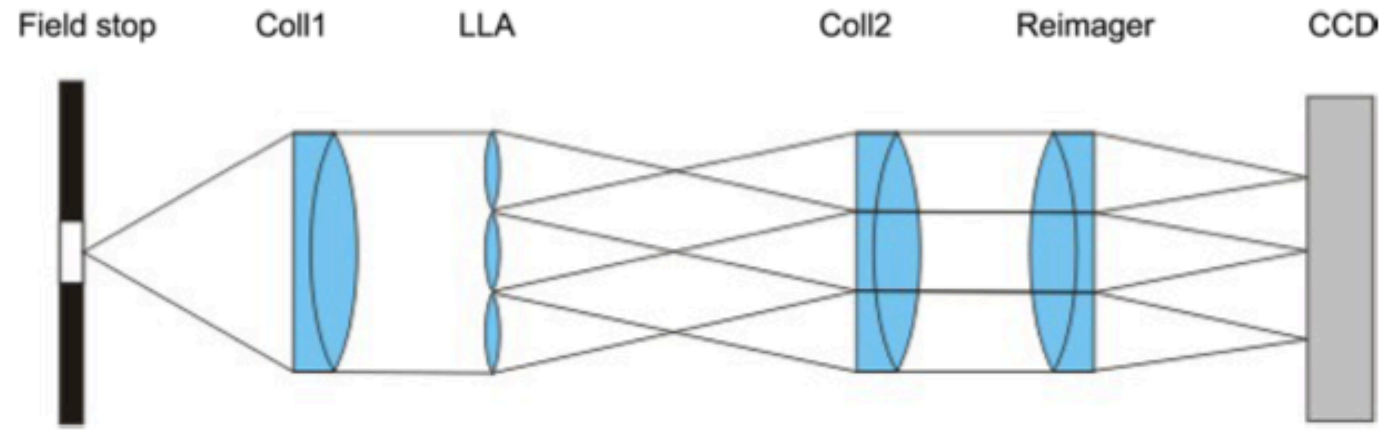
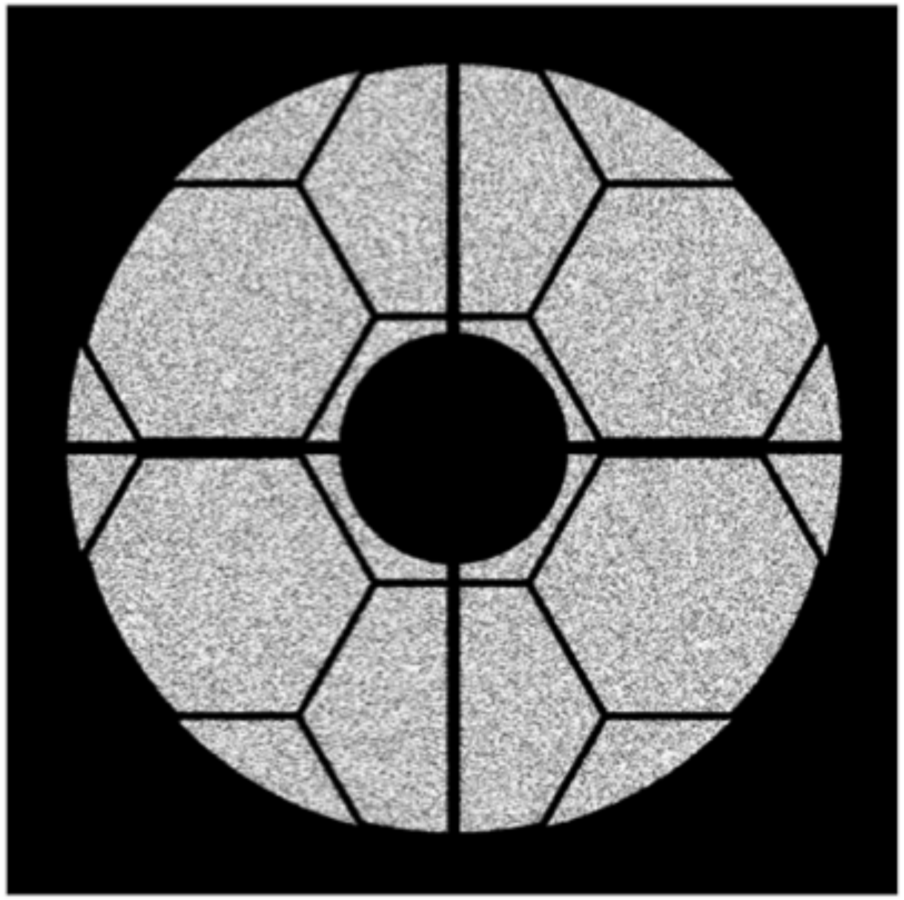


Figure 3 Scheme of the wave-front sensor of *Sunrise*. The field stop coincides with a focal plane of the telescope.

The purpose of a Shack-Hartmann array is to split up an aperture into smaller sub-apertures. Relative motion between the images formed by the Shack-Hartmann lenslets indicates wavefront distortion caused by the atmosphere.

Figure 4 Illumination pattern of the CWS lenslet array. The image of the 1 m entrance pupil provides a homogeneous illumination of the six peripheral micro-lenses, except for the (small) influence of the spiders. The central lenslet is obscured by the secondary mirror and is not used.



QUESTION: How good is the seeing at 120,000 ft?

The 2009 SUNRISE flight quantitatively measured the effects of seeing. Result: **you cannot tell that you are not in space** from the Correlated Wavefront Sensor results.

The SUNRISE Mission's Shack-Hartmann Experiment

The *Sunrise* Mission

P. Barthol · A. Gandorfer · S.K. Solanki · M. Schüssler · B. Chares · W. Curdt · W. Deutsch · A. Feller · D. Germerott · B. Grauf · K. Heerlein · J. Hirzberger · M. Kolleck · R. Meller · R. Müller · T.L. Riethmüller · G. Tomasch · M. Knölker · B.W. Lites · G. Card · D. Elmore · J. Fox · A. Lecinski · P. Nelson · R. Summers · A. Watt · V. Martínez Pillet · J.A. Bonet · W. Schmidt · T. Berkefeld · A.M. Title · V. Domingo · J.L. Gasent Blesa · J.C. del Toro Iniesta · A. López Jiménez · A. Álvarez-Herrero · L. Sabau-Graziati · C. Widani · P. Haberler · K. Härtel · D. Kampf · T. Levin · I. Pérez Grande · A. Sanz-Andrés · E. Schmidt

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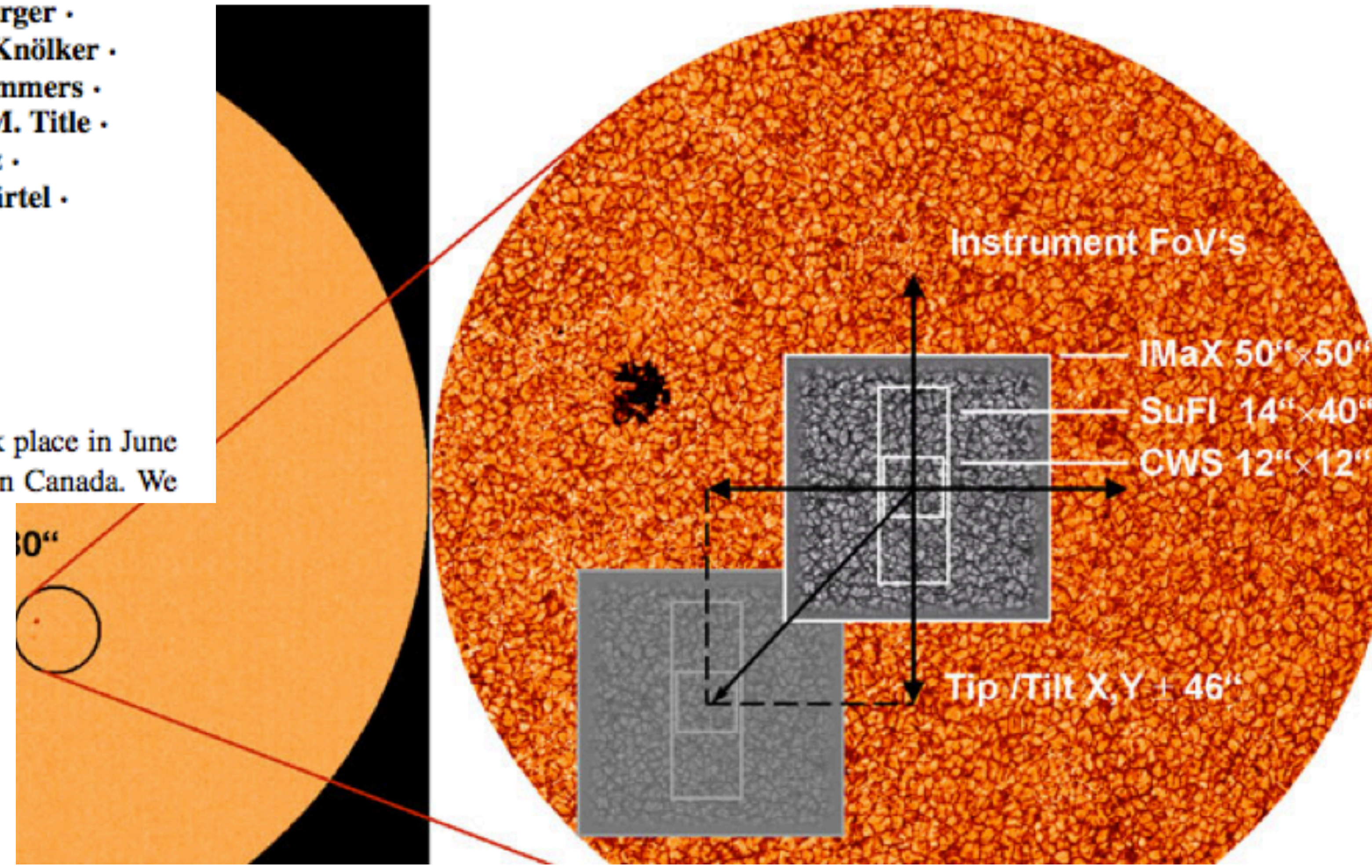
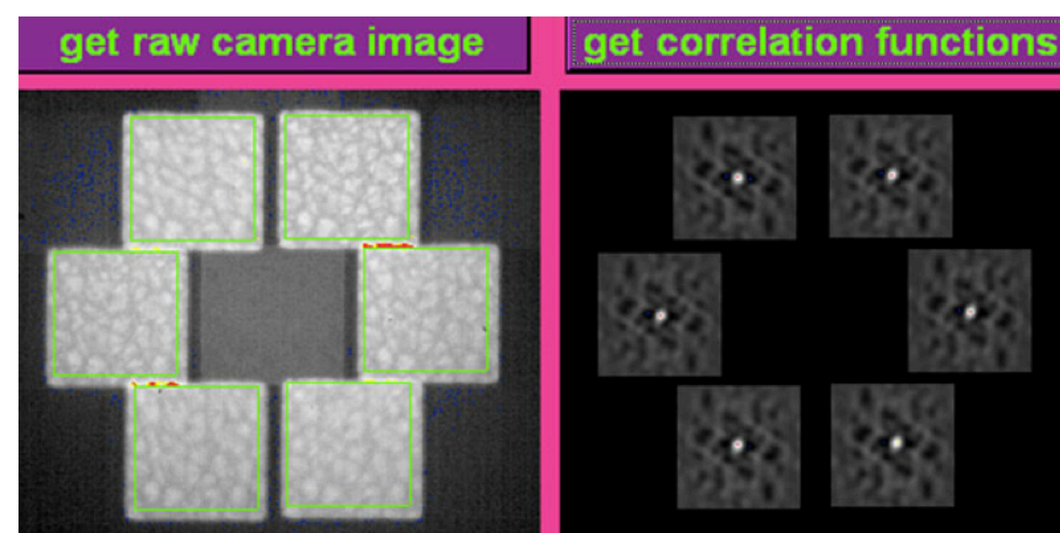
Abstract The first science flight of the balloon-borne *Sunrise* telescope took place in June 2009 from ESRANGE (near Kiruna/Sweden) to Somerset Island in northern Canada. We





QUESTION: How good is the seeing at 120,000 ft?

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Diffraction-Limited Performance from 120,000 ft

Wavelength	1 m	1.5 m	2 m
0.25 µm	0.063"	0.042"	0.031"
0.5 µm	0.126"	0.084"	0.063"
1 µm	0.252"	0.168"	0.126"

A one meter telescope in the stratosphere will provide a 0.125 arcsec point spread function (PSF) in visible wavelengths.

What about photometry?

What is the Amplitude of Scintillation at 120,000 ft?

Robert et al. Vol. 25, No. 2/February 2008/J. Opt. Soc. Am. A 379

Retrieving parameters of the anisotropic refractive index fluctuations spectrum in the stratosphere from balloon-borne observations of stellar scintillation

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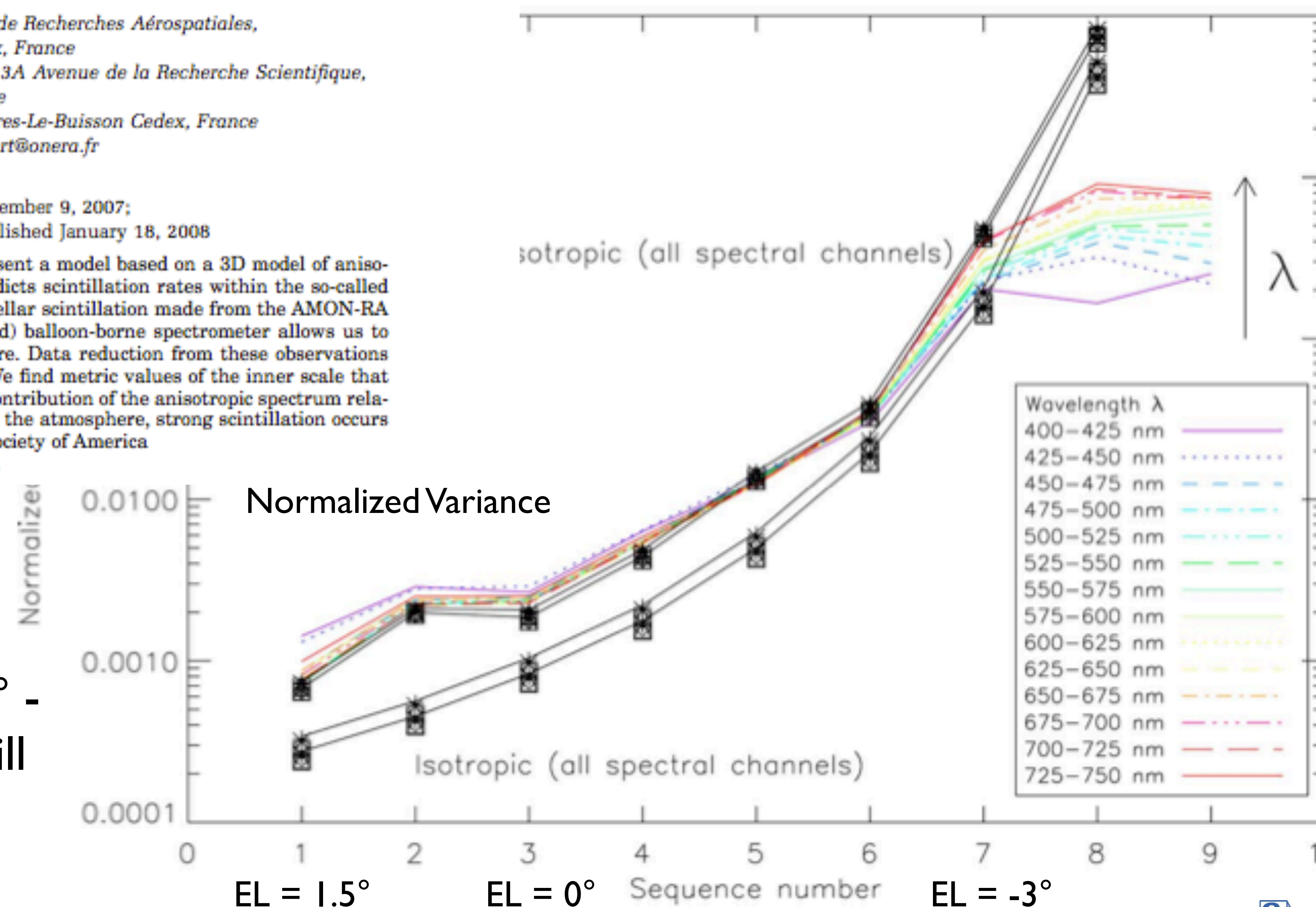
Scintillation effects are not negligible in the stratosphere. We present a model based on a 3D model of anisotropic and isotropic refractive index fluctuations spectra that predicts scintillation rates within the so-called small perturbation approximation. Atmospheric observations of stellar scintillation made from the AMON-RA (AMON, Absorption par les Minoritaires Ozone et NO_x; RA, rapid) balloon-borne spectrometer allows us to remotely probe wave-turbulence characteristics in the stratosphere. Data reduction from these observations brings out values of the inner scale of the anisotropic spectrum. We find metric values of the inner scale that are compatible with space-based measurements. We find a major contribution of the anisotropic spectrum relative to the isotropic contribution. When the sight line plunges into the atmosphere, strong scintillation occurs as well as coupled chromatic refraction effects. © 2008 Optical Society of America

OCIS codes: 010.1300, 010.1330, 010.1290, 280.0280, 120.6200.

Robert et al. (2008) fit a scintillation model to balloon-borne observations (z = 29.2 km). Their model accurately predicts scintillation (except at chords corresponding to elevation angles below 3°!).

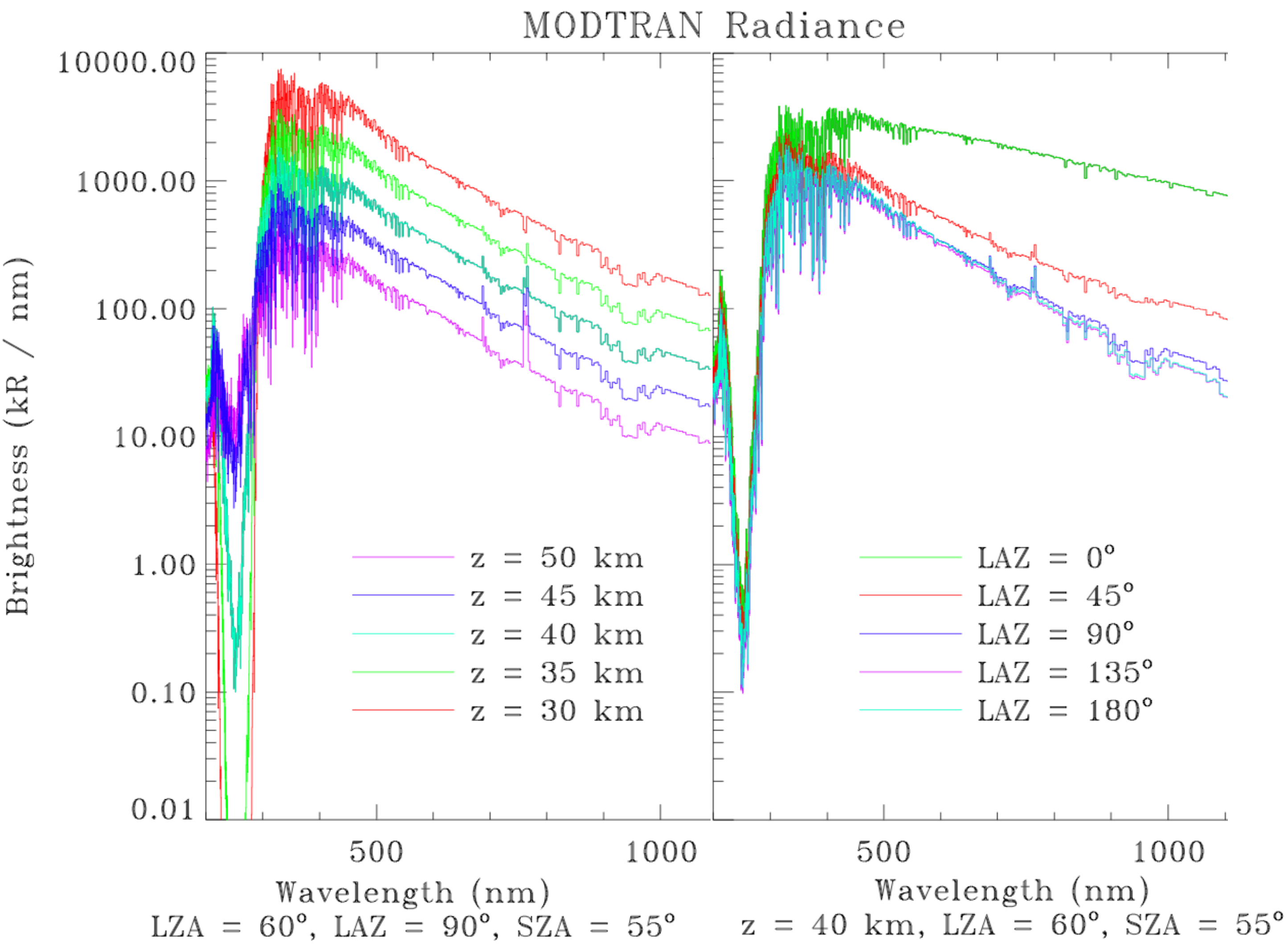


Short answer:
At astronomical elevation angles (5° - 75°) from z = 35 km, scintillation will be a negligible noise source.

What is the Daytime Sky Background at 120,000 ft?

Sky Background model:

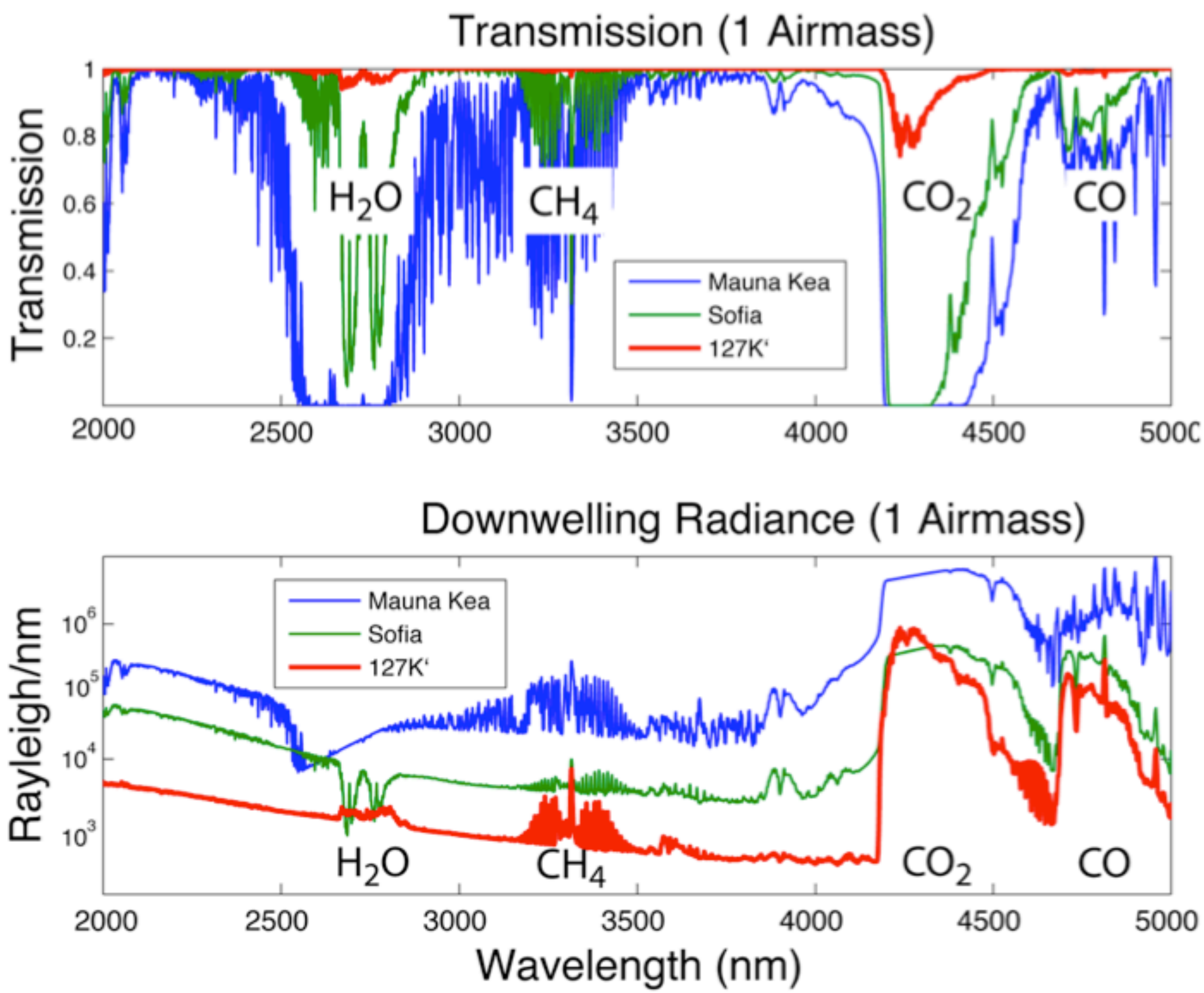
- Decreases with λ^{-4}
- Decreases by 2x for every 5km increase in altitude
- Worse at angles 45° from sun or less



On May 5, 2011 we flew an ST5000 star tracker to z = 35 km. This image from 20 min before sunrise shows significant background in visible wavelengths (about 500 nm).

Short answer: Daytime background is significant. About 100x less than from Mauna Kea. Not good for UV/Visible targets.

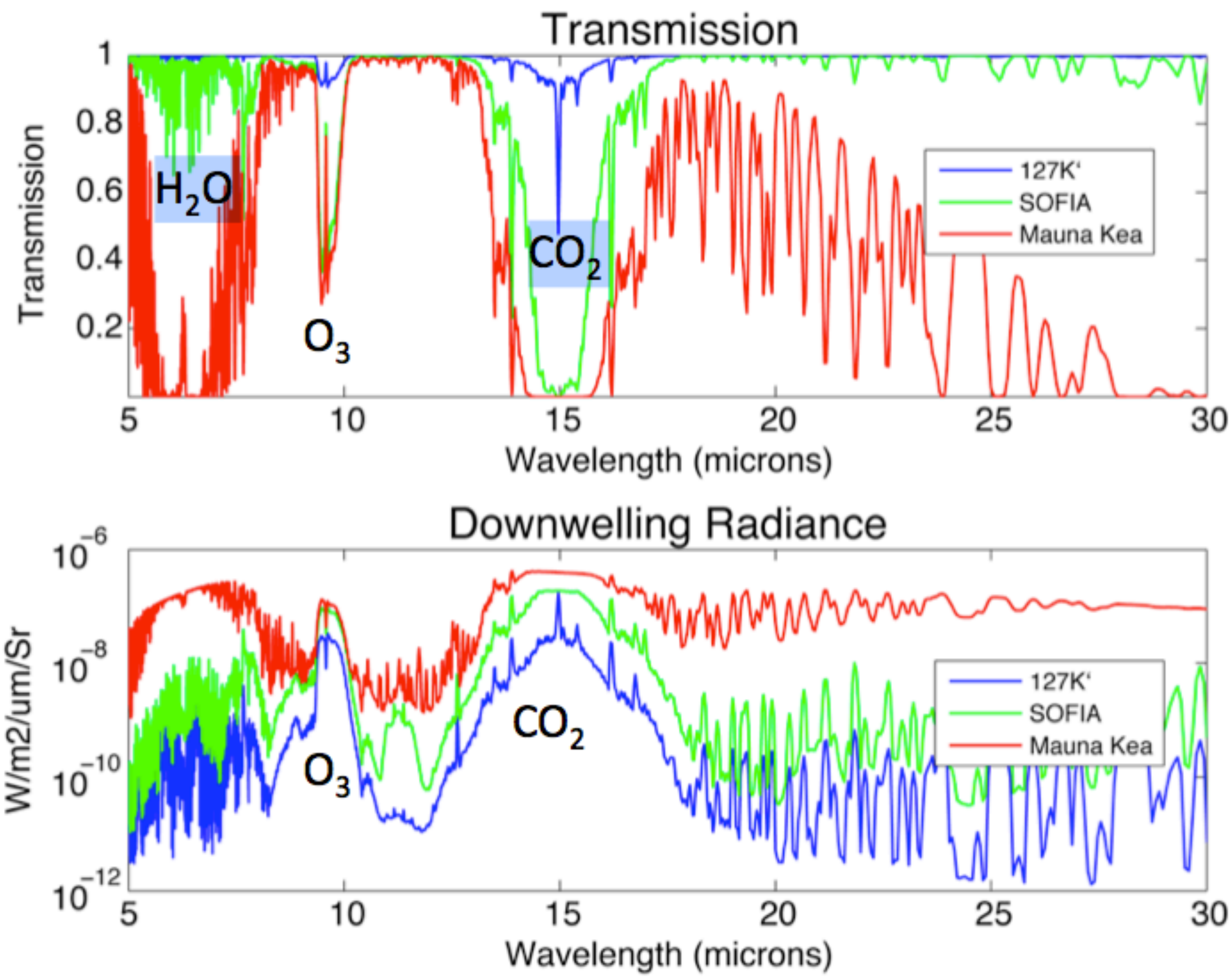
What is the Mid-Infrared Environment at 120,000 ft?



The telluric methane and water lines are almost completely absent and transmission exceeds 70% within the CO_2 band.

Considerably lower downwelling radiance than at lower altitudes, enabling longer observing for dim objects.

What is the Thermal IR Environment at 120,000 ft?



At 36 km, transmission is nearly 100% throughout the TIR and downwelling radiance is several times less than at 40K', and orders of magnitude less than at Mauna Kea. O_3 and CO_2 minimally absorb. Similar measurement advantages to Mid-IR

Summary of the near-space environment at 120,000 ft:

- ◇ Imaging: diffraction limited at λ<1µm.
- ◇ Photometry: virtually no scintillation.
- ◇ Daytime: A problem at λ<1µm.
- ◇ Low telluric absorptions.
- ◇ Low IR backgrounds.

Balloon-borne telescopes have an important role at λ<1µm. This is a regime that is only accessible to the Hubble Space Telescope. It not covered by ground-based adaptive optics systems.

PART TWO: THE ST5000 TEST FLIGHT

Question: Why fly a star tracker?
Answer: If the stratosphere supports DIFFRACTION LIMITED imaging, balloon platforms need to be pointed at a fraction of the diffraction limit.

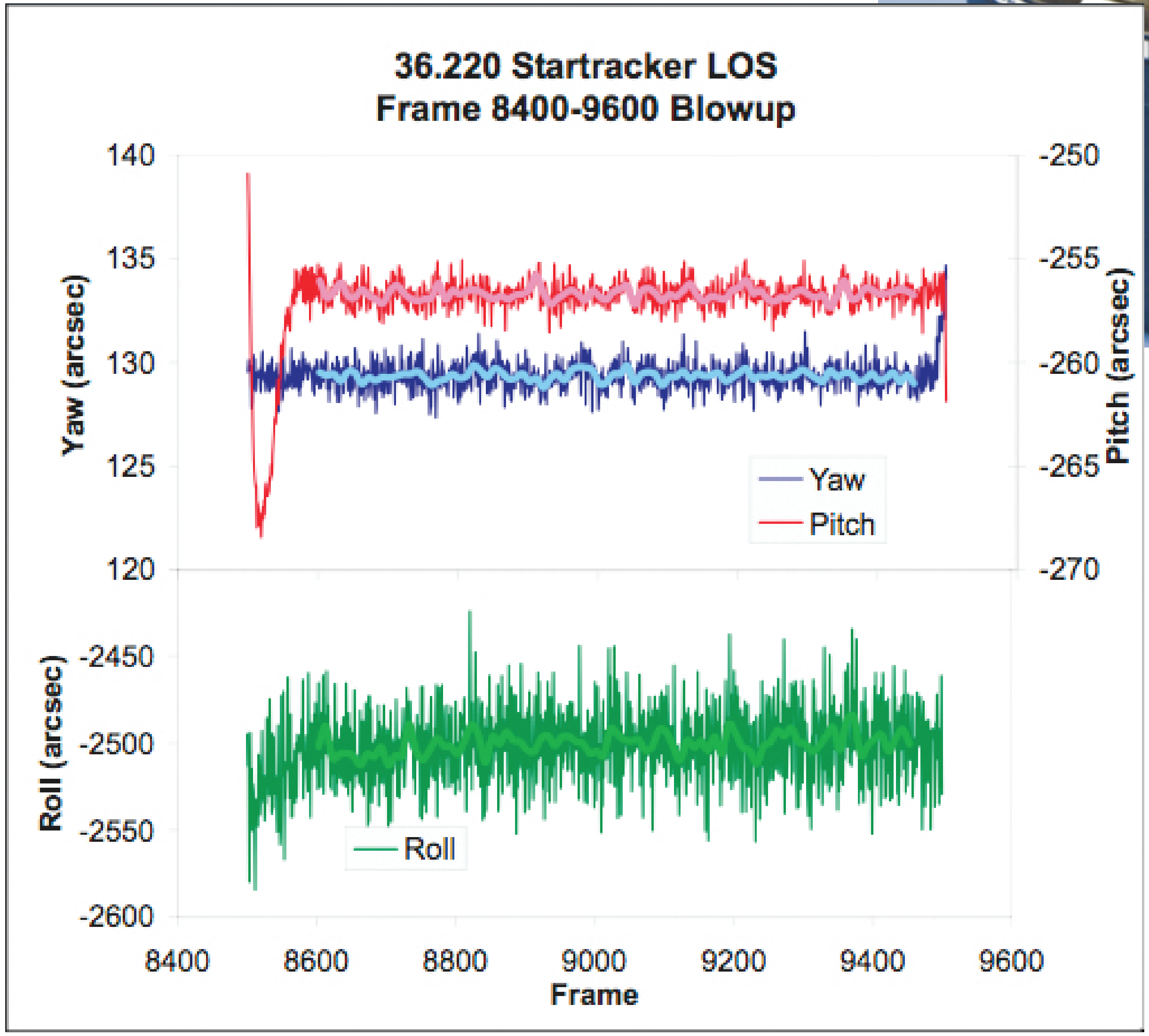
This presents two challenges:
- Getting the pointing error, and
- Implementing the corrections.

The Star Tracker 5000 might be a reasonable way to address the first problem. The ST5000 was developed at the University of Wisconsin. It has become the standard star tracker for NASA's sounding rocket program.
Cost: less than $100K per unit.

The ST5000 Star Tracker

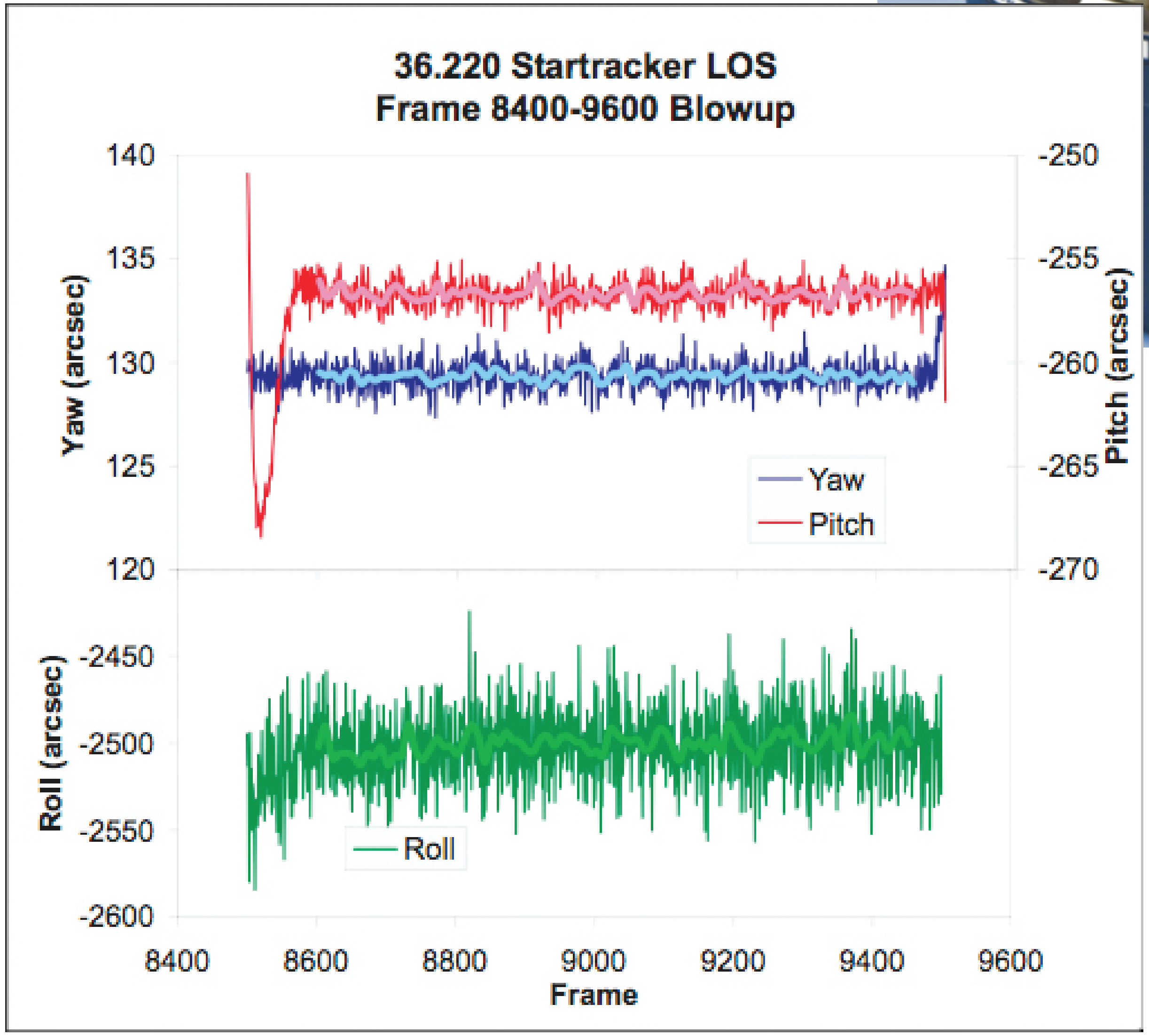
- Developed by the University of Wisconsin-Madison/Space Astronomy Laboratory
- Used by NSROC/Flown on many sounding rockets
- Achieves Lost in Space solution in 1 s.

- 10 Hz attitude updates
- Weight: 9 lb; Power: 12 W
- Accuracy of pointing solution: 0.5”
- 50 mm F/0.95 lens
- 7°x5° FOV, 35” per pixel



The ST5000 Star Tracker

- **Question**: ST5000 pixels are ~35” in size. How are yaw & pitch characterized at the 0.5” level?
- **Answer**: (a) Centroids give subpixel resolution, and (b) typically track 24 stars per frame.



Four Questions for the ST5000 Balloon Test Flight

- Would the ST5000 work in the stratosphere?
- How well would the ST5000 track?
- What motion would make the ST5000 fail?
- Would the ST5000 work in daylight?

We originally scheduled a flight from Palestine, TX in August 2010 on the HASP platform (High Altitude Student Payload – <http://laspace.lsu.edu/hasp>), but NASA had a temporary flight moratorium that would push us back to summer 2011.

HASP payload

SIP (NASA's Support Instrument Package)

Ballast

Near Space Corporation ST5000 Balloon Test Flight

To fly without delay, we contracted with Near Space Corporation (Tillamook, OR) to integrate and fly our payload.

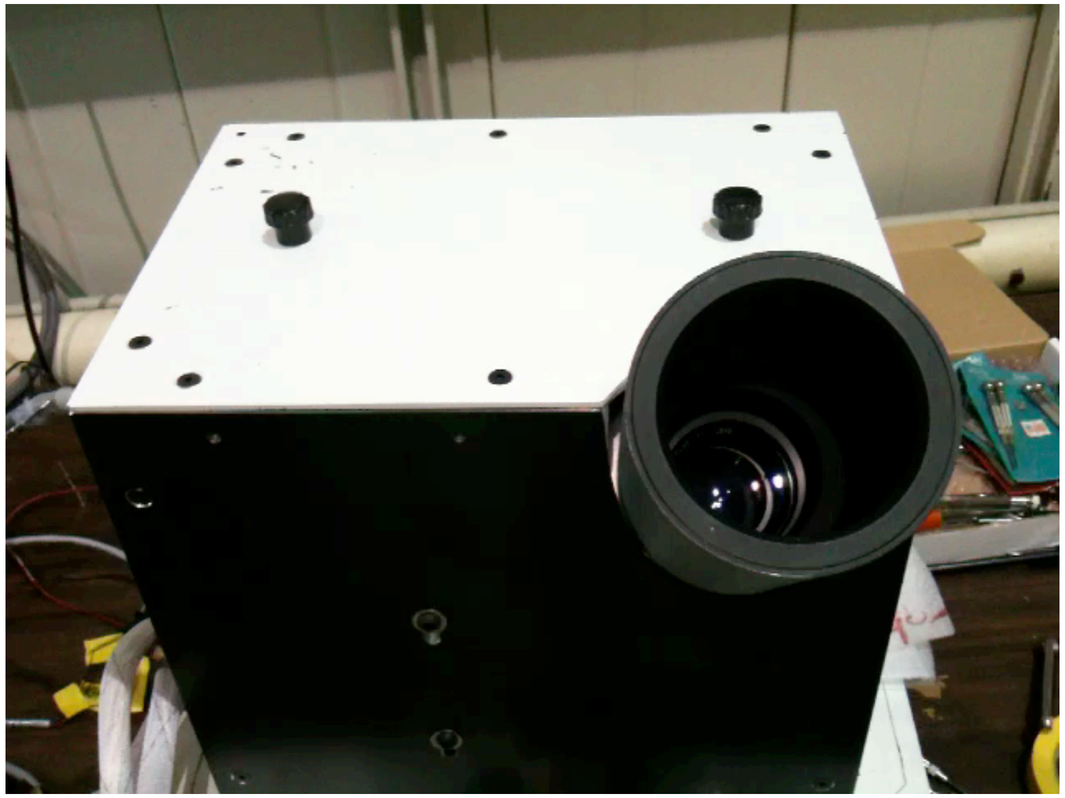
- Payload Integration at Near Space Corp.

- Used two iridium modems for command uploads only (one for the ST5000, another for the NSC command module.

- VHF data downlink

- Finally launched from Madras, Oregon on May 5, 2011.

- Balloon released at 1:30 AM, 100 minute ascent, at float past sunrise, termination near 6 AM.



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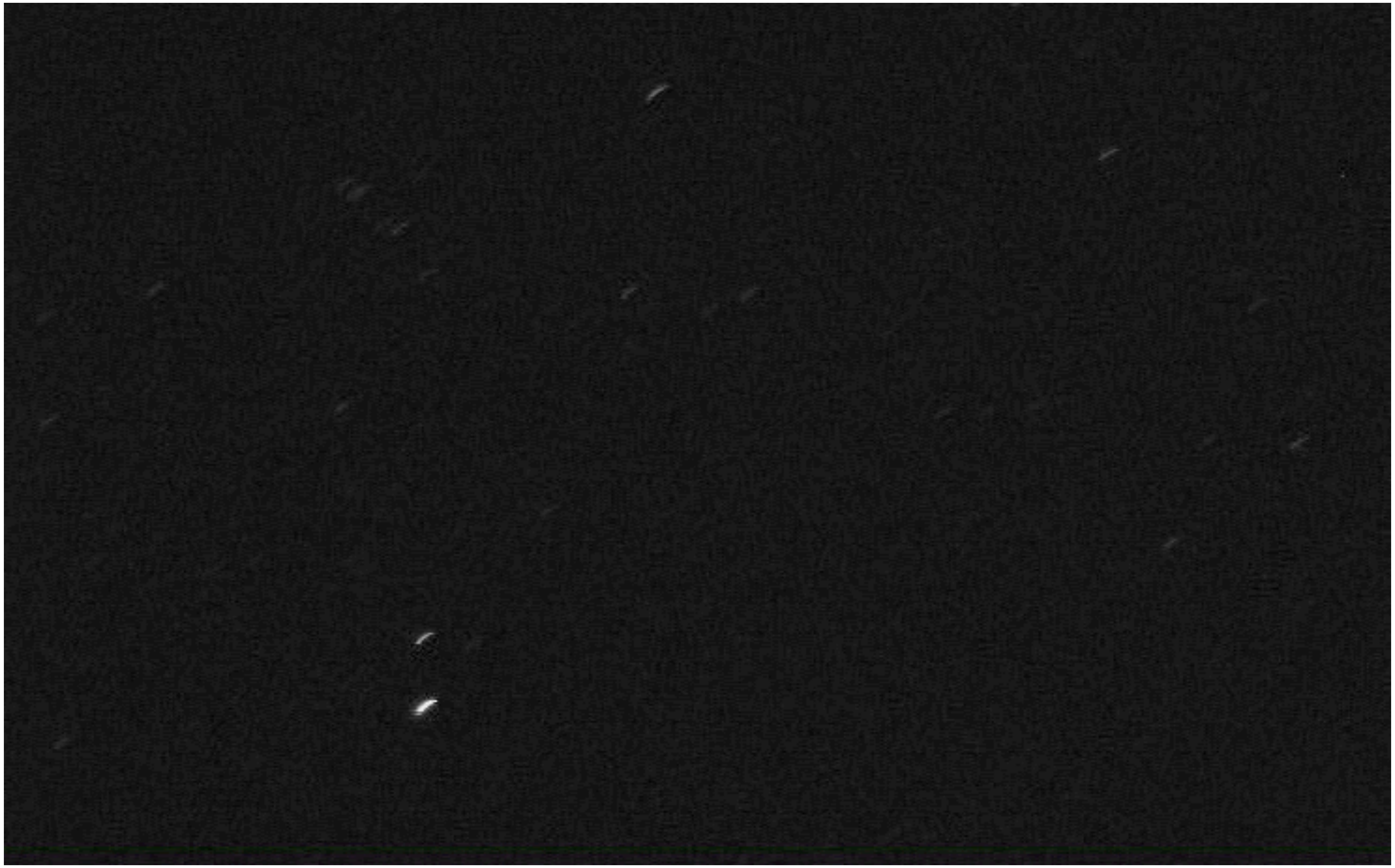
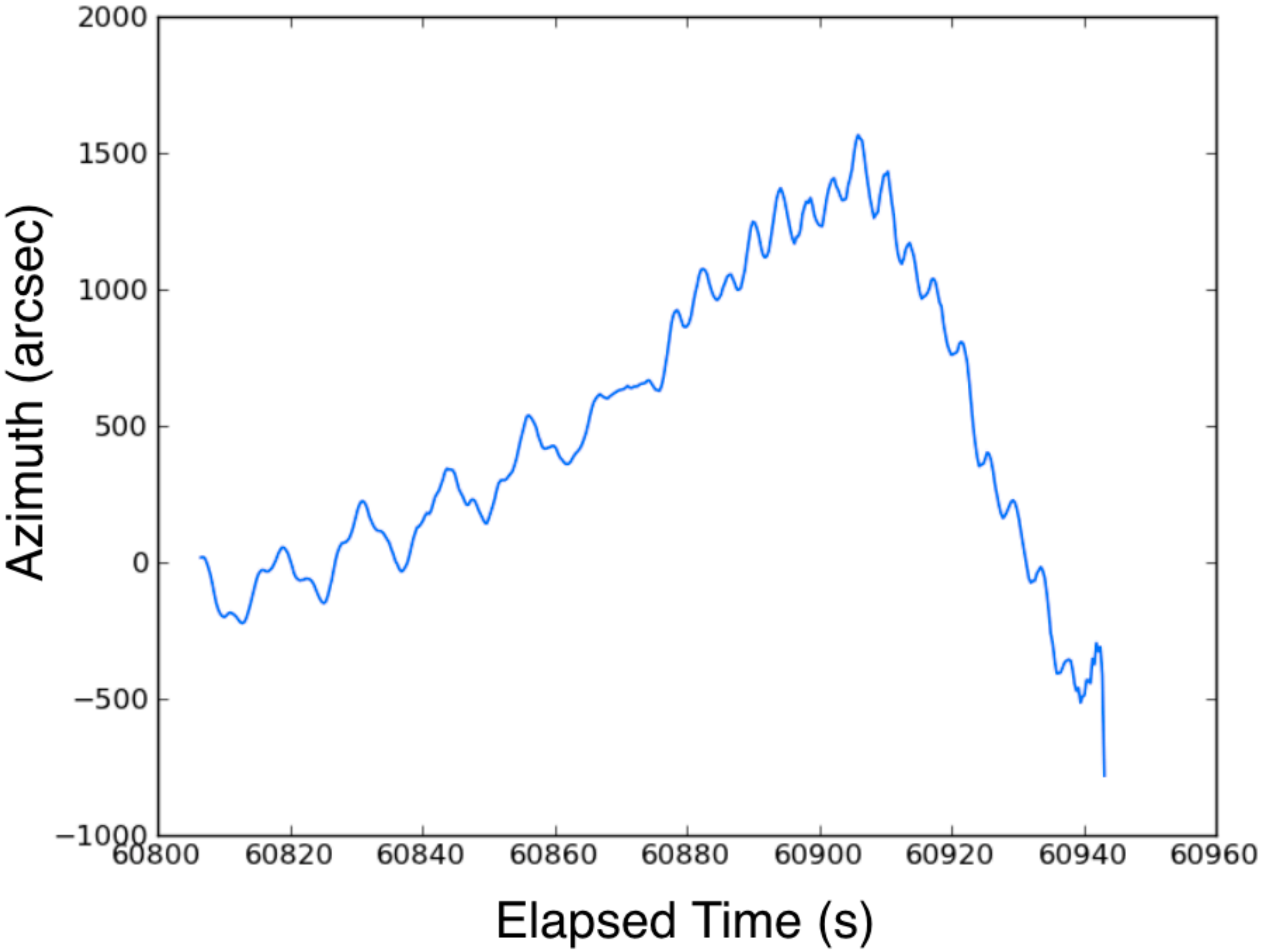
Flight Results

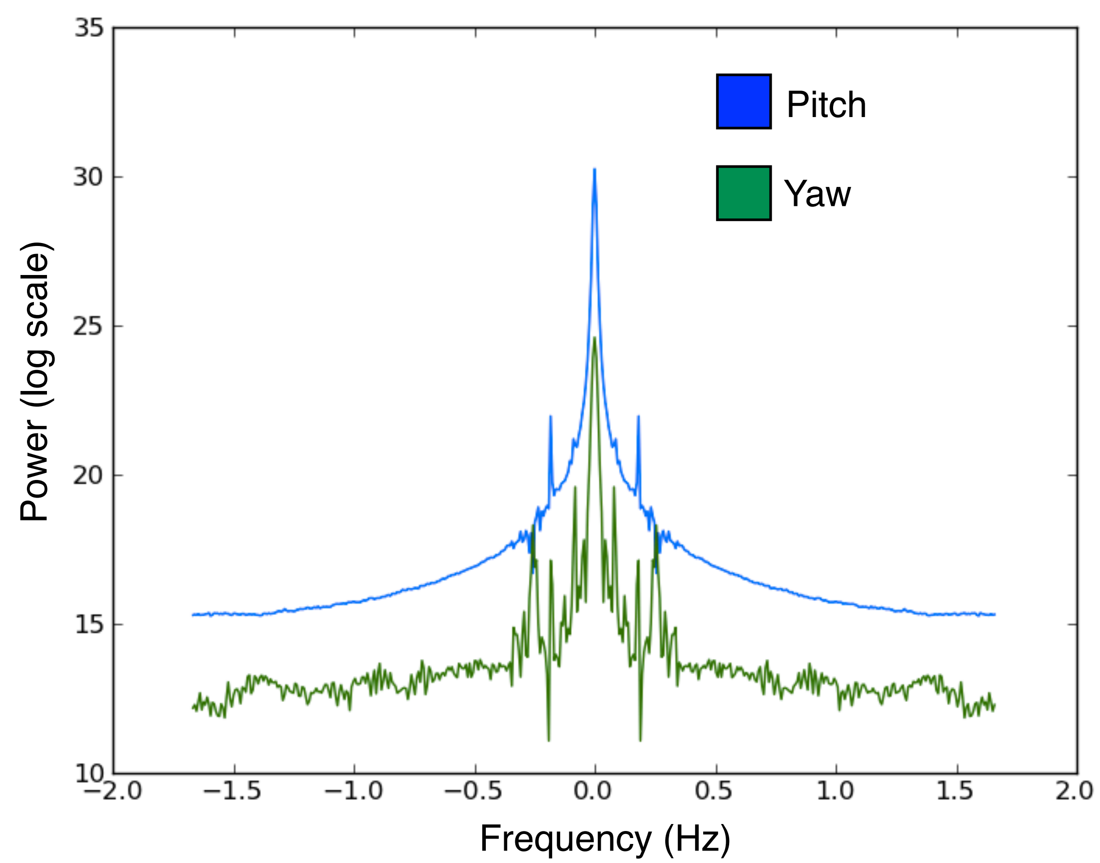


Video recorded during ascent and float phases. Considerable gondola motion - especially during ascent - but many moments of sufficient stability allowed tracking and lost-in-space solutions.

Flight Results

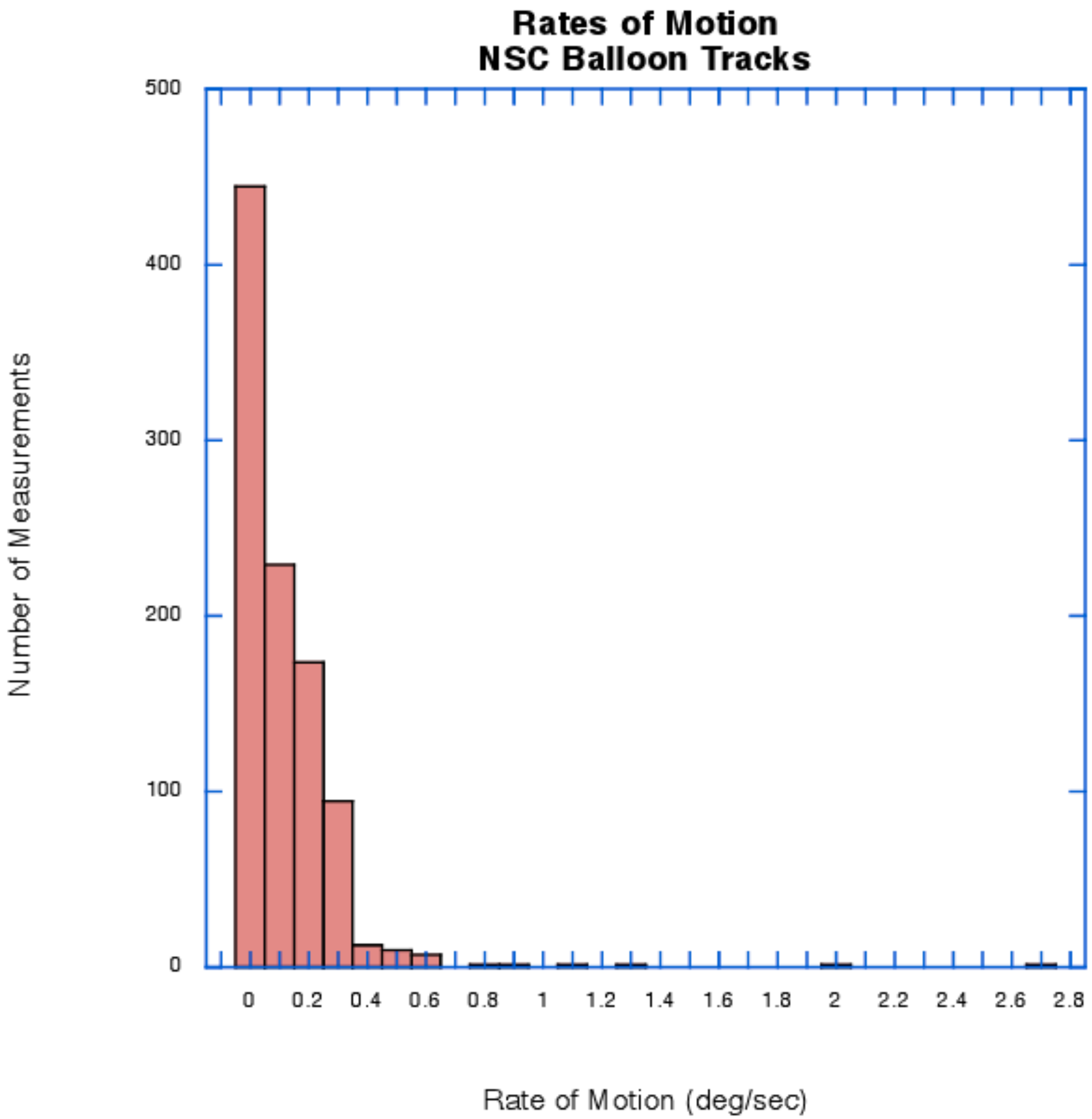


A two-minute sequence from the ST5000's "yaw" readout (nearly equivalent to the azimuth in this case).



The unperturbed balloon environment is fairly benign. Twisting and pendulum modes have most power at 0.3 Hz or less. Should be easy to correct with a fine steering mirror.

Flight Results



Question: What are the maximum rates at which the ST5000 can track?

Answer: about 0.4 to 0.6 degrees per second.

We know this from the maximum recorded rates between pairwise orientations observed when the ST5000 was tracking.

Flight Results

Daytime Performance: The ST5000 stopped identifying stars during twilight, about 30 minutes before sunrise.

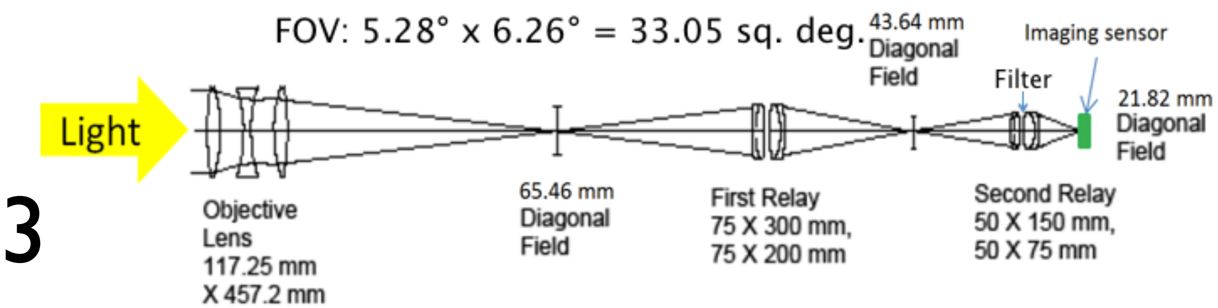
PART THREE: FUTURE WORK

There are two ways to improve daytime performance:

- Infrared detector (less sky background)
- Finer platescale (less background per pixel). Requires a longer focal length and a larger detector.

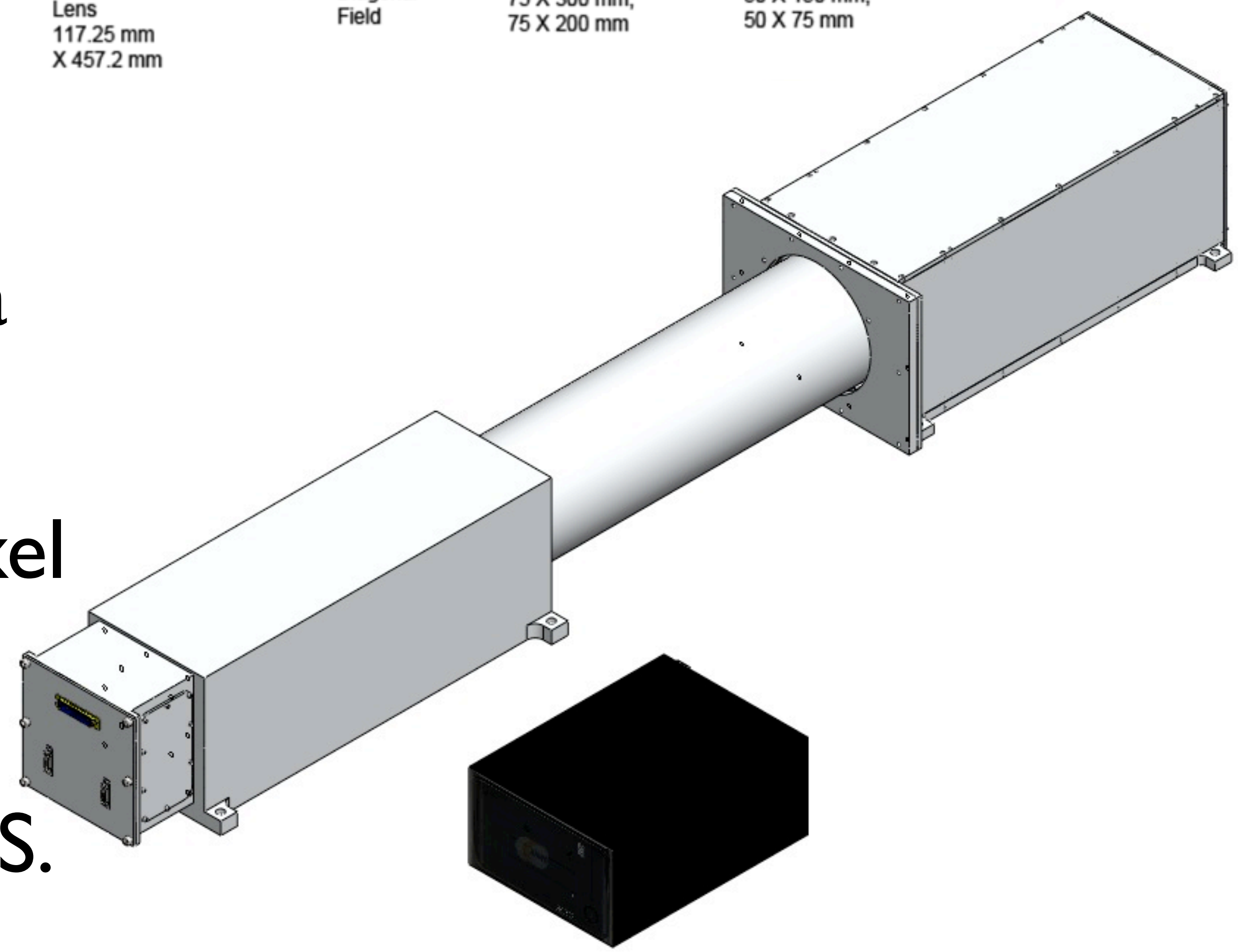
DAYSTAR (University of Colorado)

We are supporting a CU Aerospace Senior Capstone project to build a new front end for the ST5000 (new optics & detector).



- Optics: focal length = 133 mm, F/1.3 telescope. Two internal stops to decrease scattered background, plus a baffle on the end.

- Detector: a 2500 x 2000 pixel sCMOS detector with low read noise (less than 2 e-). Full frame read out at 30 FPS.



Jed Diller	Aaron Holt	Michael Skeen
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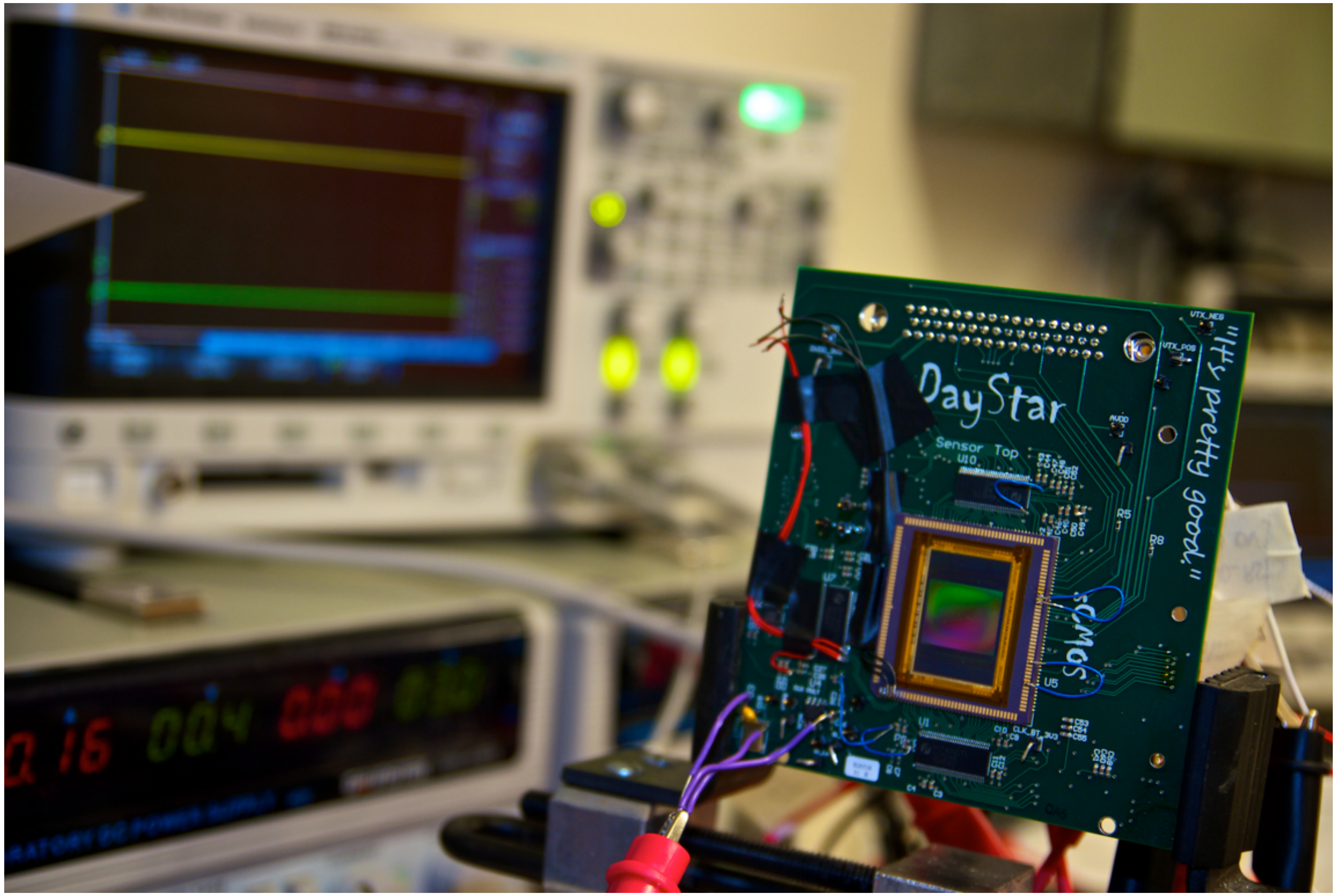


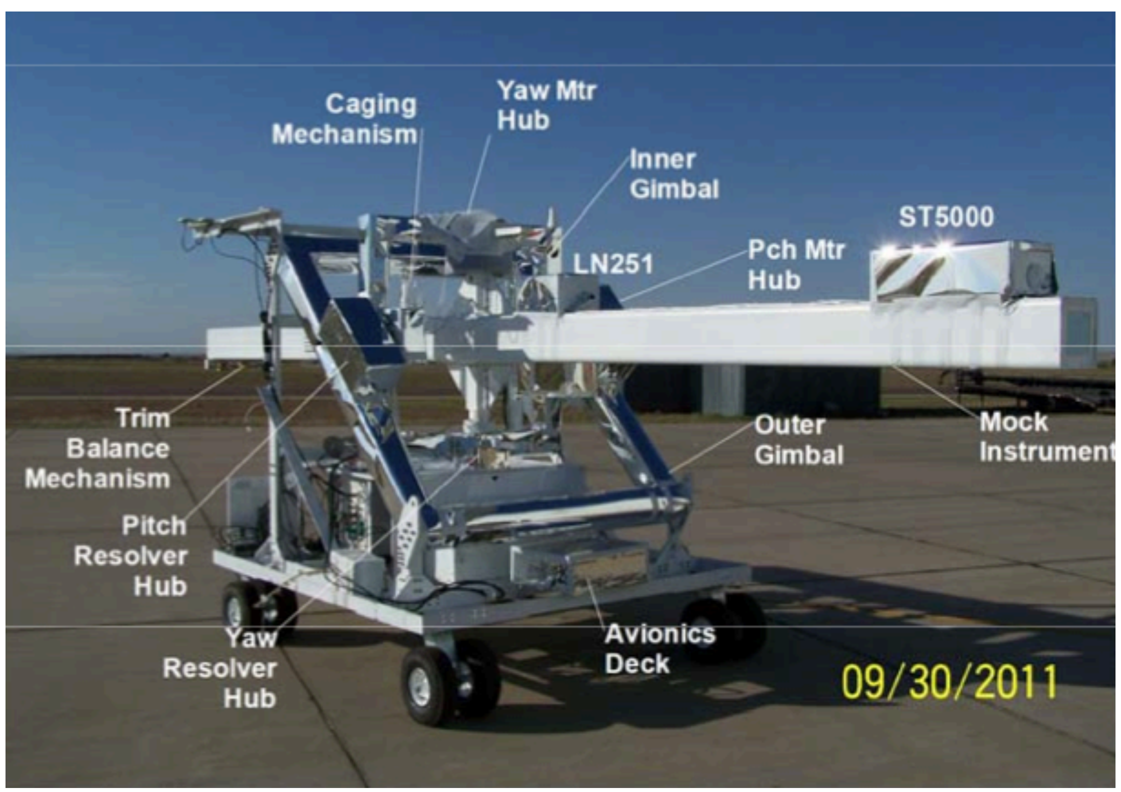
A recent picture of the sCMOS sensor undergoing testing at CU.

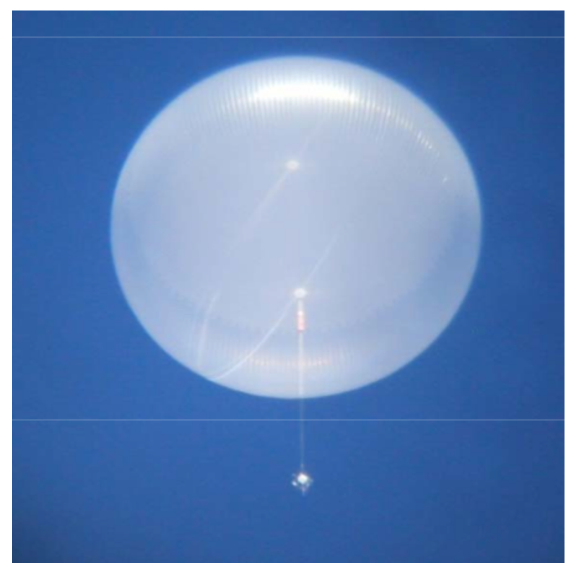
The finer platescale will improve the rms tracking to 0.1" (at night) and 1" (during day). Same FOV as the current ST5000, same ST5000 back-end. First tests expected in early April.

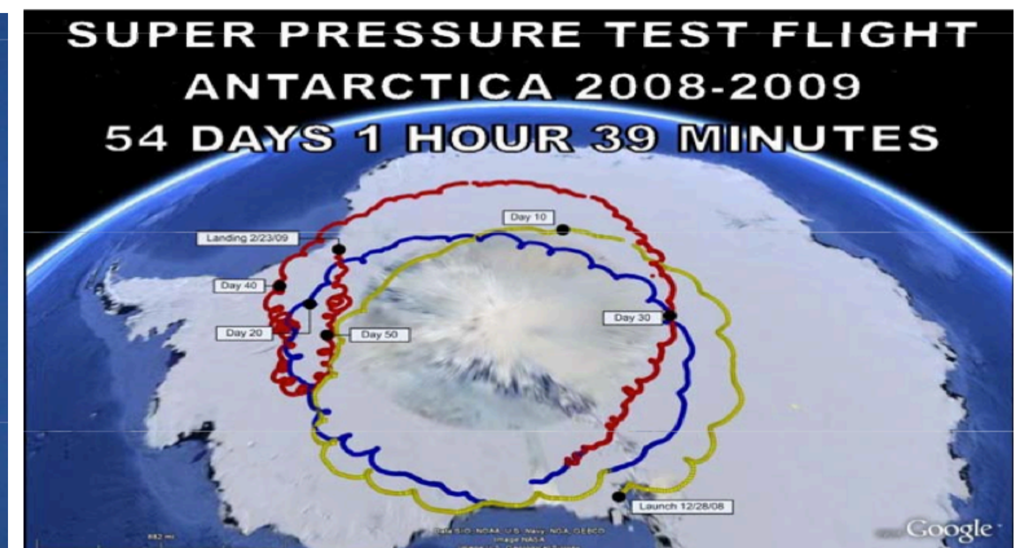
Jed Diller	Aaron Holt	Michael Skeen
Kevin Dinkel	Tyler Murphy	Nick Truesdale
Zach Dischner	Sara Schuette	Andrew Zizzi

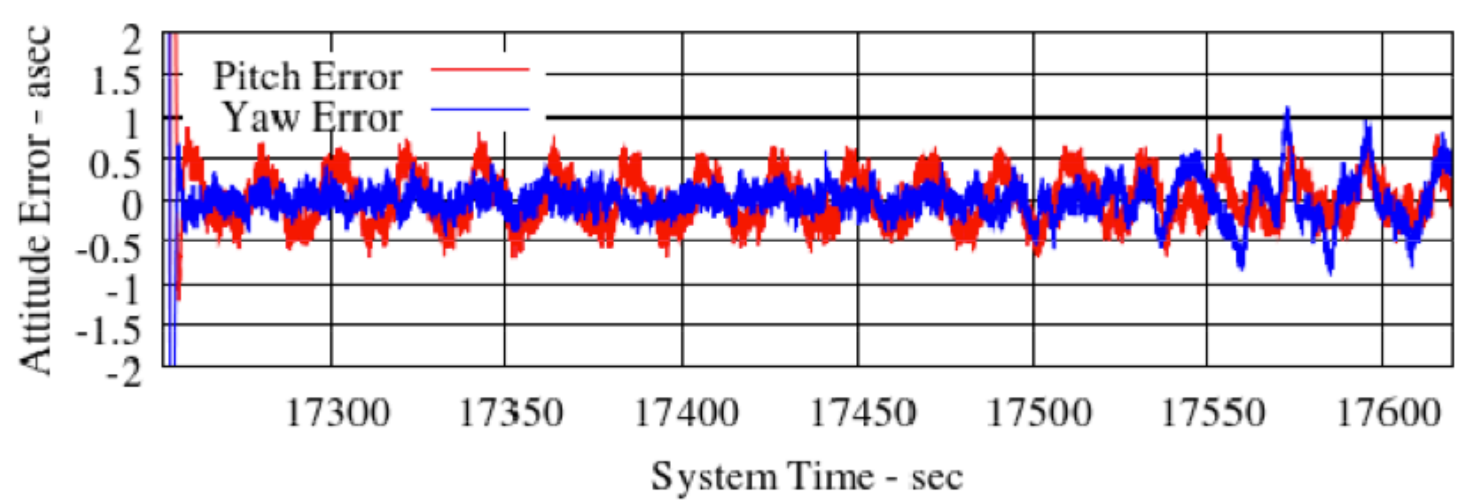
Recent Developments in NASA's Balloon Program

- Development of SUPER-PRESSURE balloons for extended day/night missions. NASA's 18 MCF balloon capable of lifting 5000 lbs suspended payload.
- 40 and 50 day missions have already flown. You can now propose for 100 DAY MISSIONS (circumglobal missions launched from New Zealand). Example: GUSSTO mission.
- The Wallops Arc-Second Pointing System (WASP) was successfully flown on a balloon on Oct 9, 2011. A 1500 lb, 24 ft mock telescope was held on target with rms yaw and pitch pointing errors of 0.25".
- *Near Space Corporation* is now a NASA launch provider. *No cost* to PIs through the Flight Opportunities program (like the NASA/BPO flights). NSC has the ability to support rapid launches of smaller payloads.







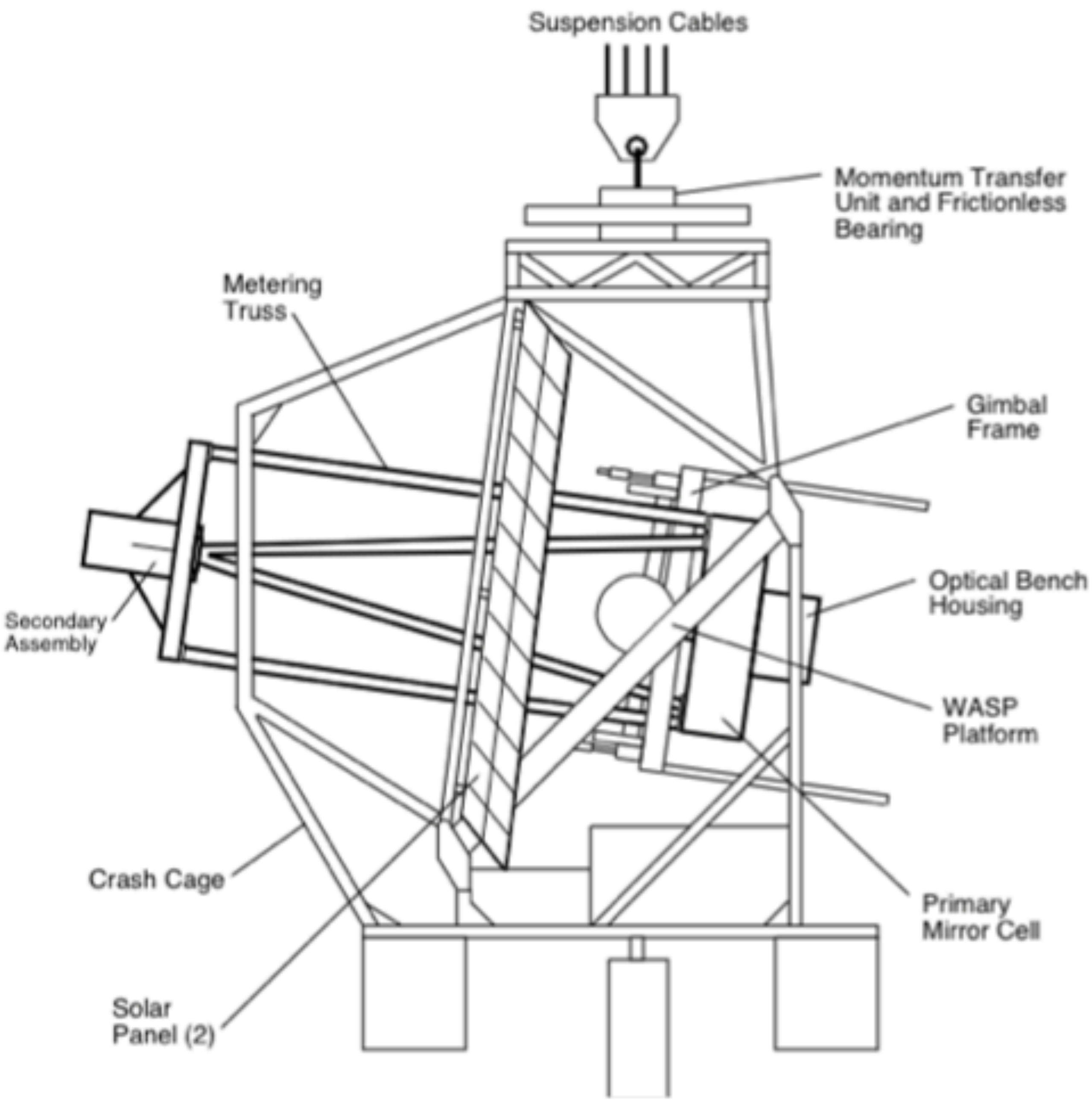


Summary

- Will the ST5000 work on a stratospheric balloon? **YES.**
- How will it perform? **0.5” (rms)**
- What rates of motion will make it fail? **0.5° s^{-1}**
- What sky brightnesses will make it fail? **30 min before sunrise**
- **FUTURE WORK** includes DAYSTAR for use on NASA’s ultra-long duration balloons. We will try to piggyback a DAYSTAR test on the next WASP engineering flight.

A Strawman Planetary Payload

From Young et al. 2011, "Venus Stratoscope: A Balloon-Borne Campaign to Study Venus' Atmosphere and Surface," submitted to NASA/Planetary Astronomy.



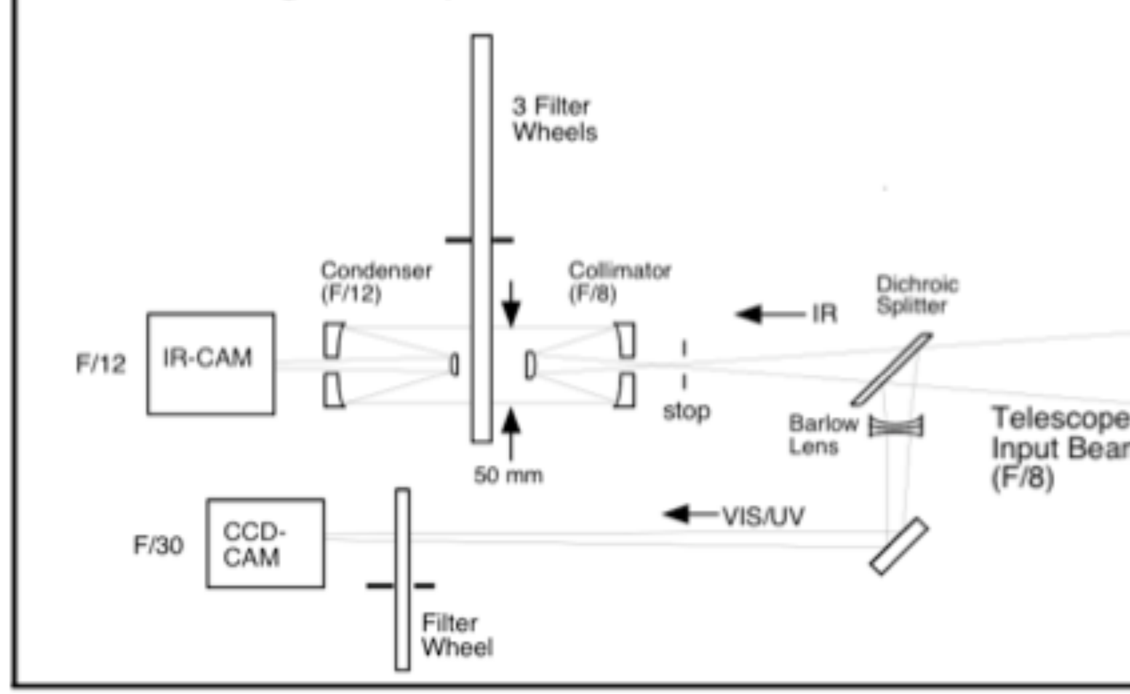
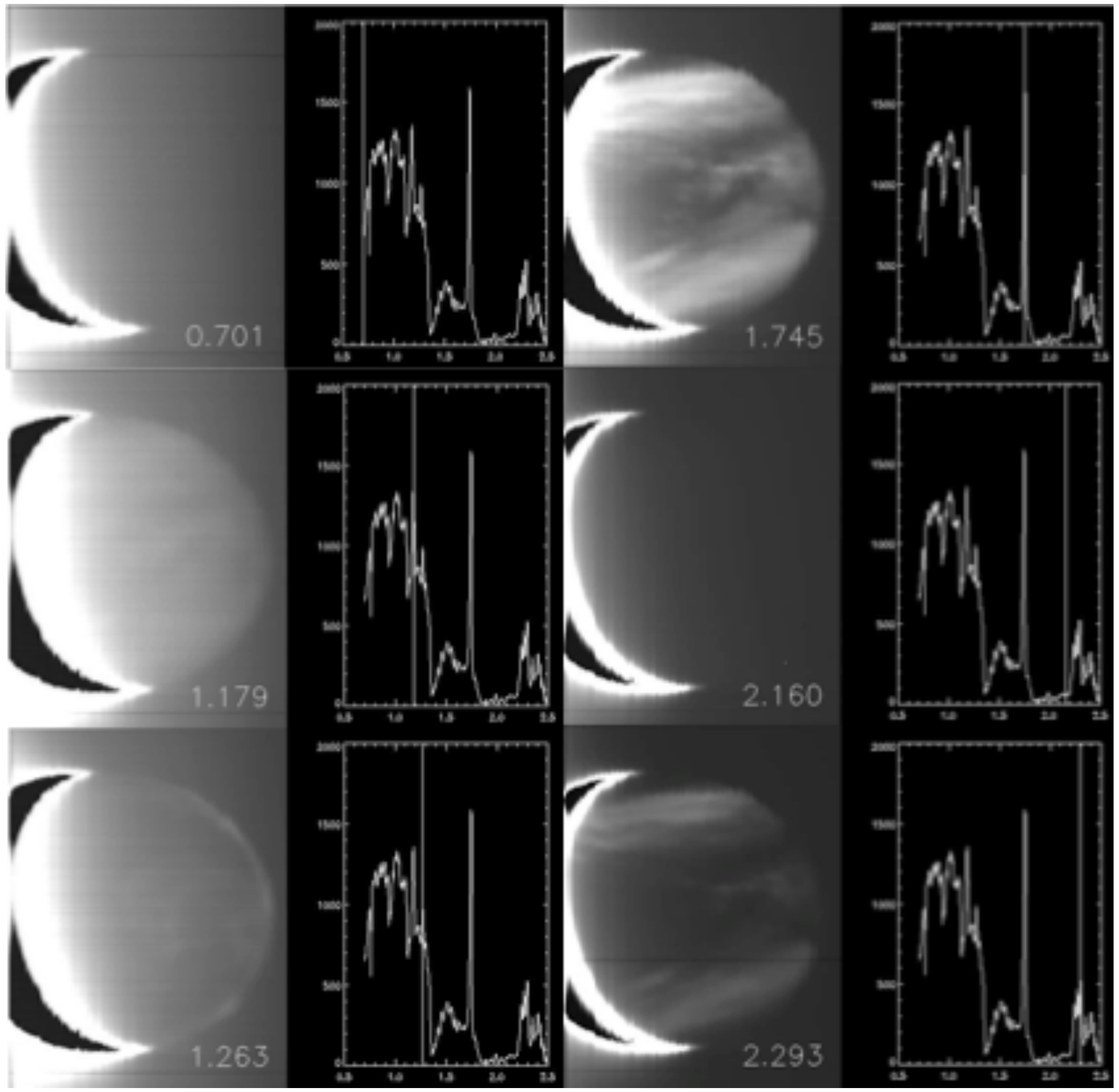


Fig. 10 Optical Bench Schematic

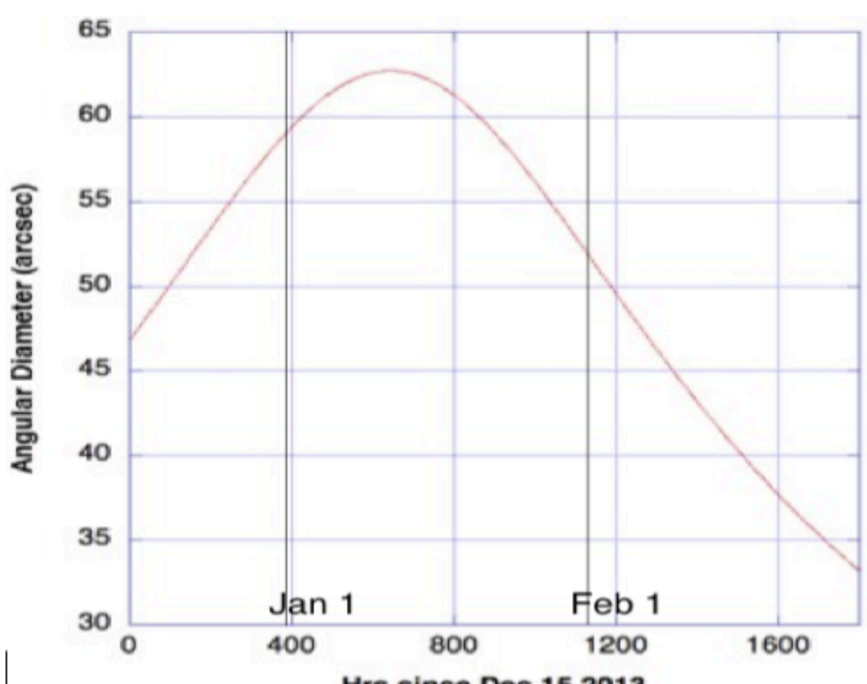
- One meter aperture - fits in WASP.
- Two cameras, IR (F/12) and CCD (F/30)
- Fast exposures (0.2 s), no Fine Steering Mirror. Over 90% of images should be diffraction limited (because of WASP).
- Estimated flight duration: 3 - 8 weeks. Estimated Cost (build, fly, recover): $3.85M

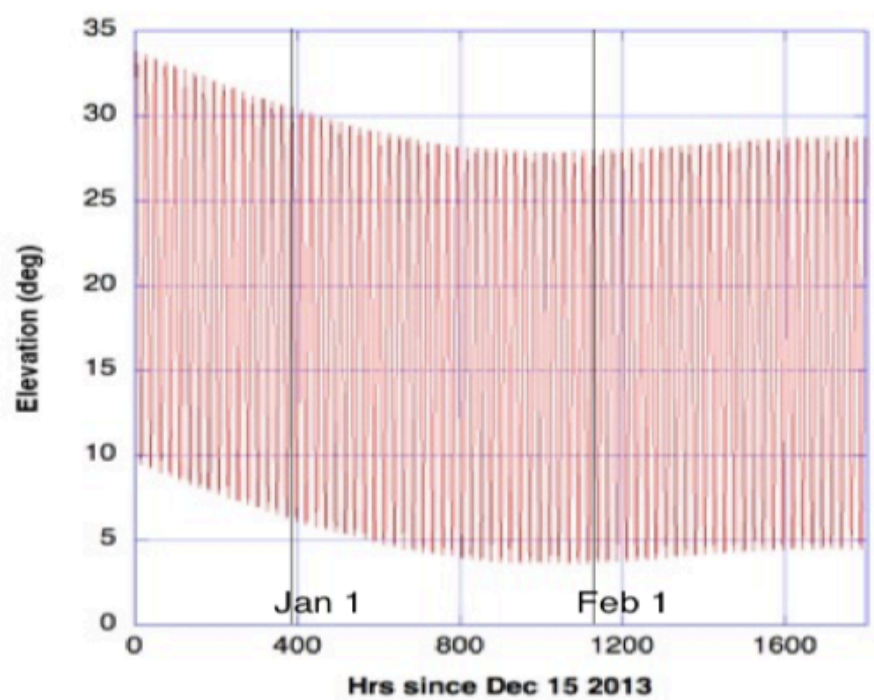
A Strawman Planetary Payload

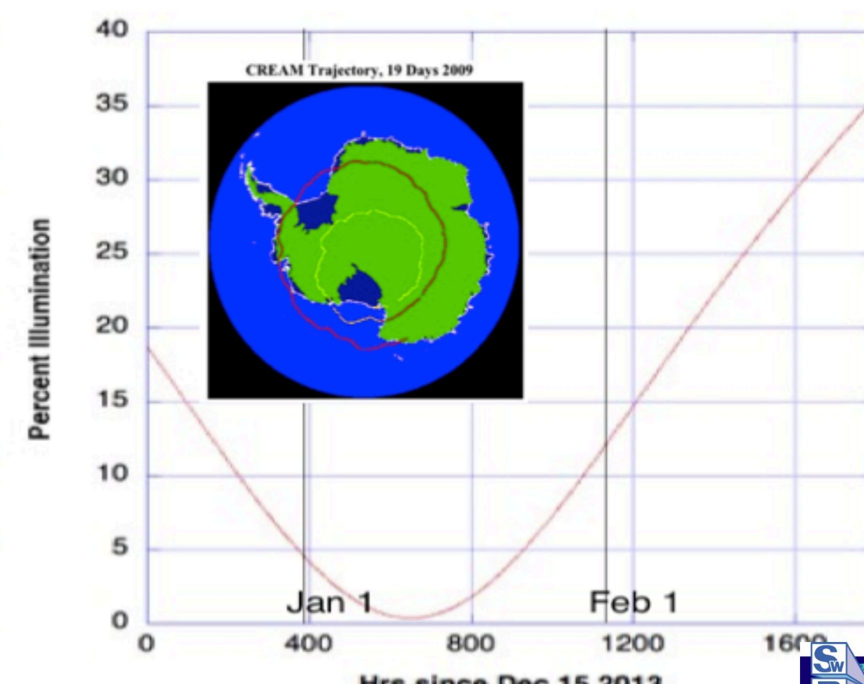


Venus from a stratospheric telescope:

- Frequent opportunities (every 19 months).
- Imaging at 1.74 μm shows lower cloud deck, shorter wavelengths determine surface emissivities.
- Wavelengths within 2.25 - 2.45 μm window: trace gas retrievals, determine cloud properties.
- Jan 2014: Venus will be continuously visible from Antarctica. Fits with NASA's existing Antarctica program.
- Resolution at 1.74 μm is 0.44" for a 1-m telescope (88 km on Venus). Cloud tracking to recover winds with 2 m/s precision.







More High-Resolution Targets

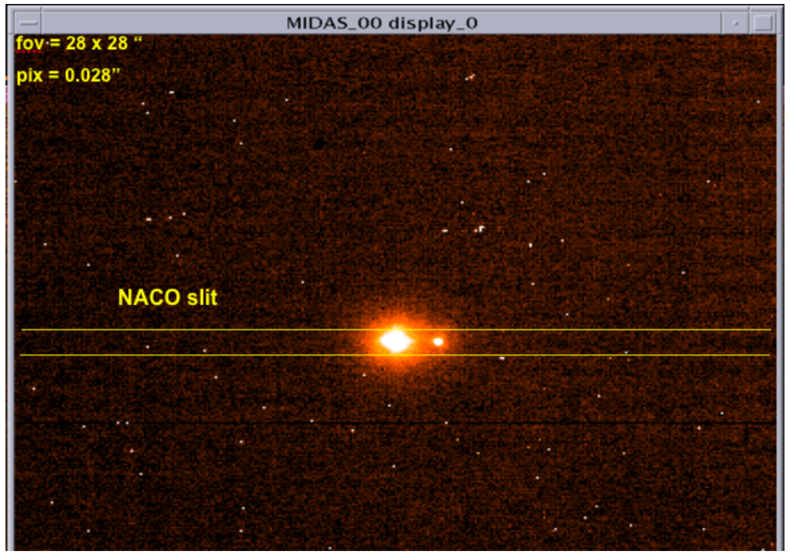


Fig 1. Spatially resolved spectroscopy of Pluto & Charon from the VLT/ NACO. Protopapa et al. 2010

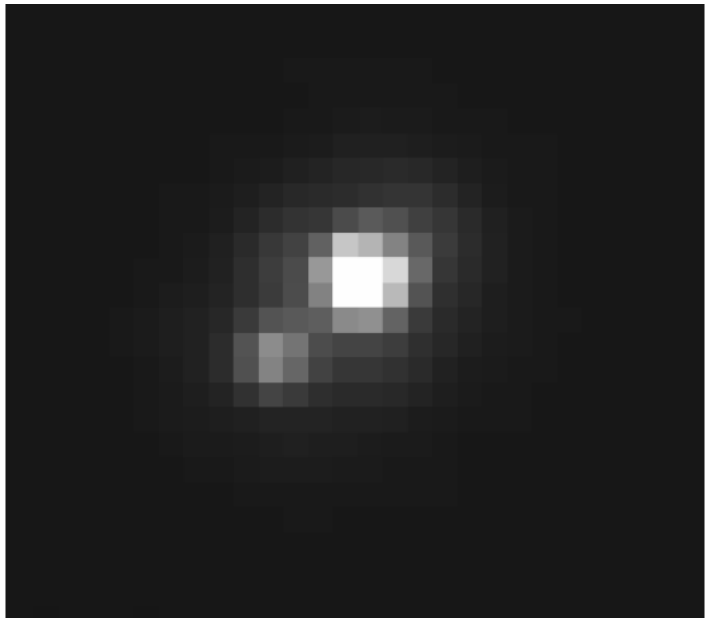


Fig 3. HST/HRC discovery of the binary centaur (42355) 2002 CR_{46} with 300 sec of on-target integration. Noll et al. 2006.

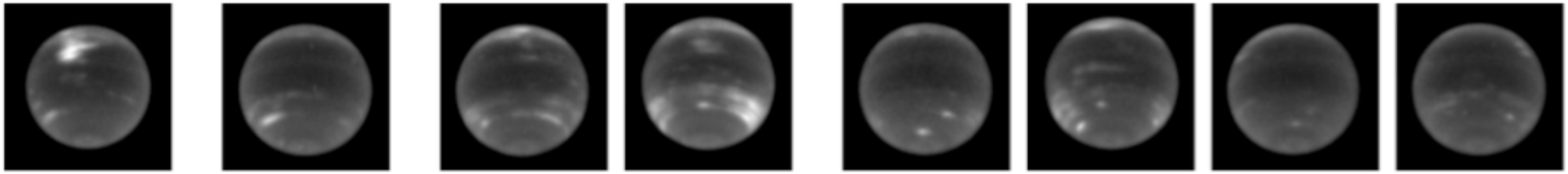


Fig. 2 Neptune (HST) in the 0.619 μm filter of WFPC2 in 1994, 1997, 2001-2002 and 2004-2007 (left to right).

Some Broad Science Goals:

- Understanding basic weather on giant planets: long-term monitoring of the giant planets at wavelengths shortward of 1.0 μm.
- Clean PSFs: finding & observing faint objects, often next to bright objects. Goals include the understanding of formation scenarios (asteroids, centaurs, TNOs, satellites and comets), ring/ satellite systems, separate spectroscopy of close binaries, and discovery of faint NEOs.
- Astrometry: vastly improved occultation predictions (e.g., for TNOs), NEO orbit determination.

Balloon Science Opportunites: A simple 1-m telescope in the stratosphere has a 0.12” diffraction limit, outperforming every telescope shortward of 1 μm except for HST.

Cost-Effectiveness of Balloon-borne Missions

Balloon launches are less expensive than spacecraft launches – our comprehensive cost for a balloon flight from NSC (payload integration, launch, flight operation and payload recovery: $70K).

Balloon missions are less expensive than GROUND-BASED operations. Example: one night on a Keck telescope was valued at $107K in a recent NSF/TSIP proposal. Balloons can achieve science unavailable to ground-based sites (diffraction-limited resolution at visible & UV wavelengths, plus sensitivity to wavelengths normally obscured by telluric absorption).

Consider a $4M balloon mission that flies for 40 days (equivalent to 40 nights): cost from Keck is MORE ($8.5M) than the balloon mission. And if you can re-use the balloon payload, the cost-advantage is even more dramatic