HST-Like Performance from Balloon-borne Telescopes

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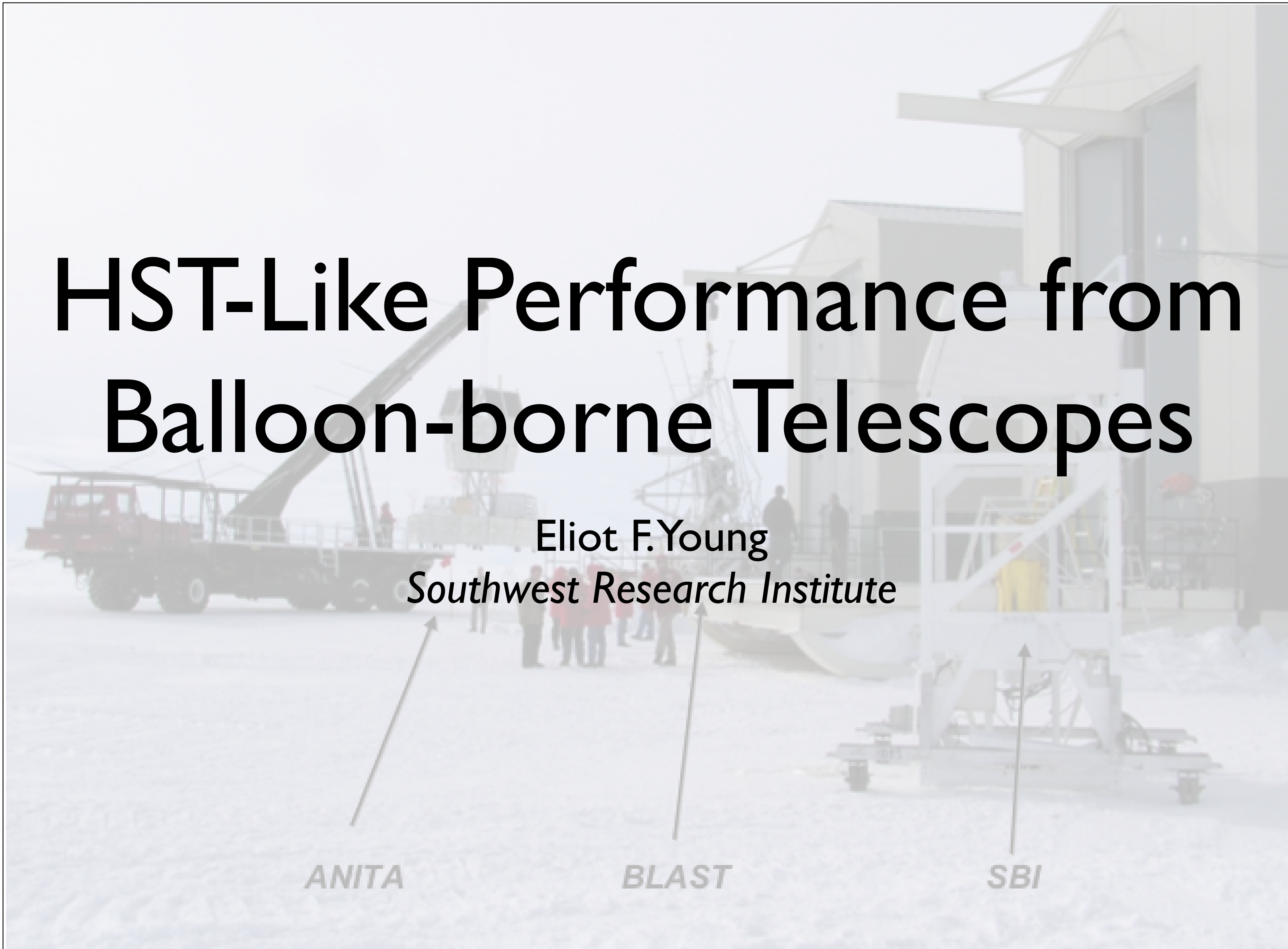
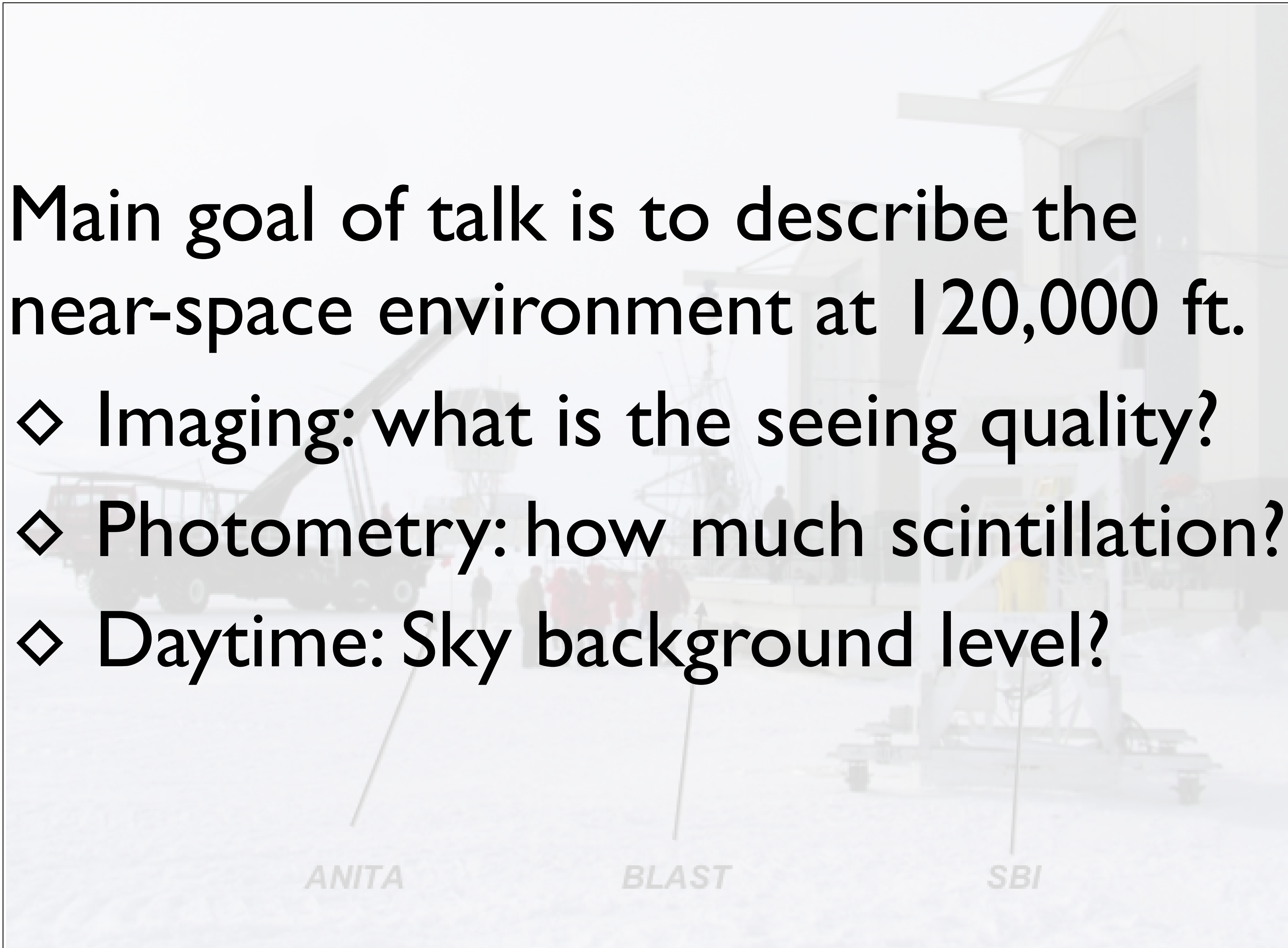


Main goal of talk is to describe the near-space environment at 120,000 ft.

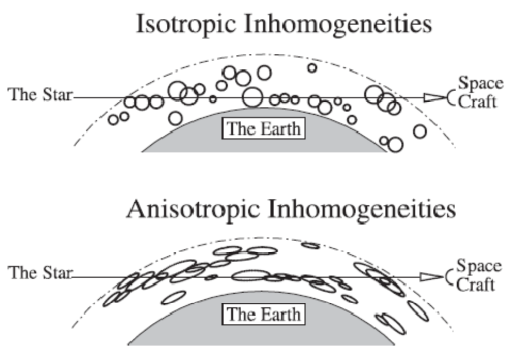
- ◇ Imaging: what is the seeing quality?
- ◇ Photometry: how much scintillation?
- ◇ Daytime: Sky background level?



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

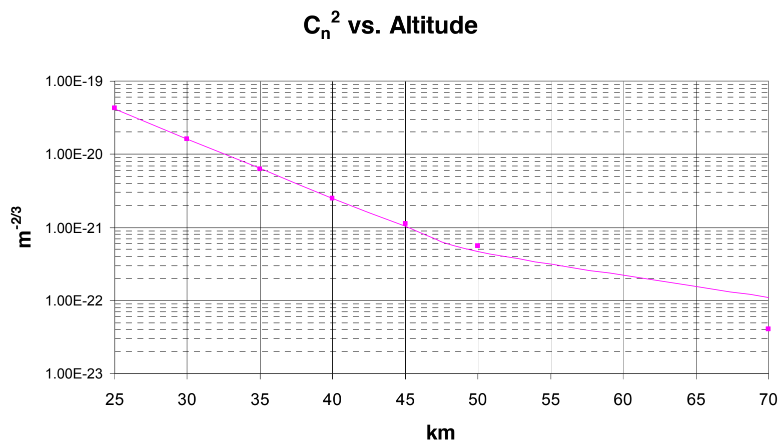
Natural Seeing

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/>

The SUNRISE Mission's Shack-Hartmann Experiment

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THE SUNRISE BALLOON-BORNE OBSERVATORY

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

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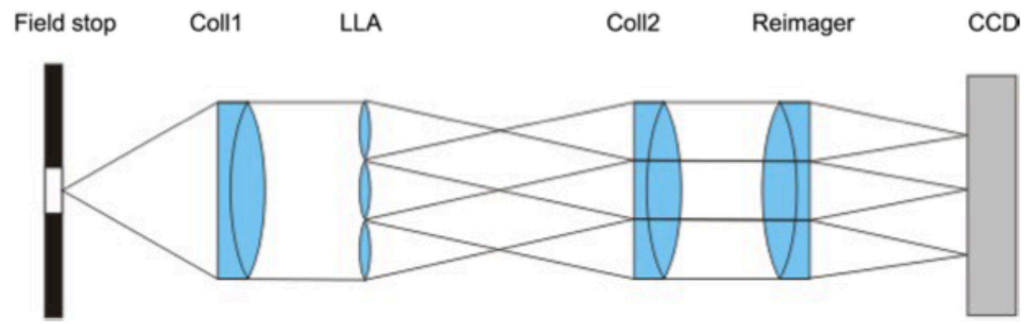
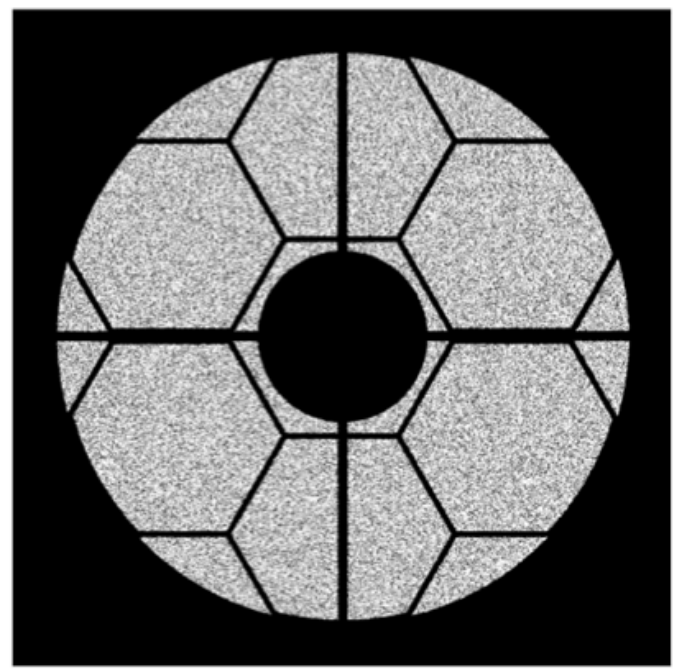


Figure 3 Scheme of the wave-front sensor of *Sunrise*. The field stop coincides with a focal plane of the telescope.

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

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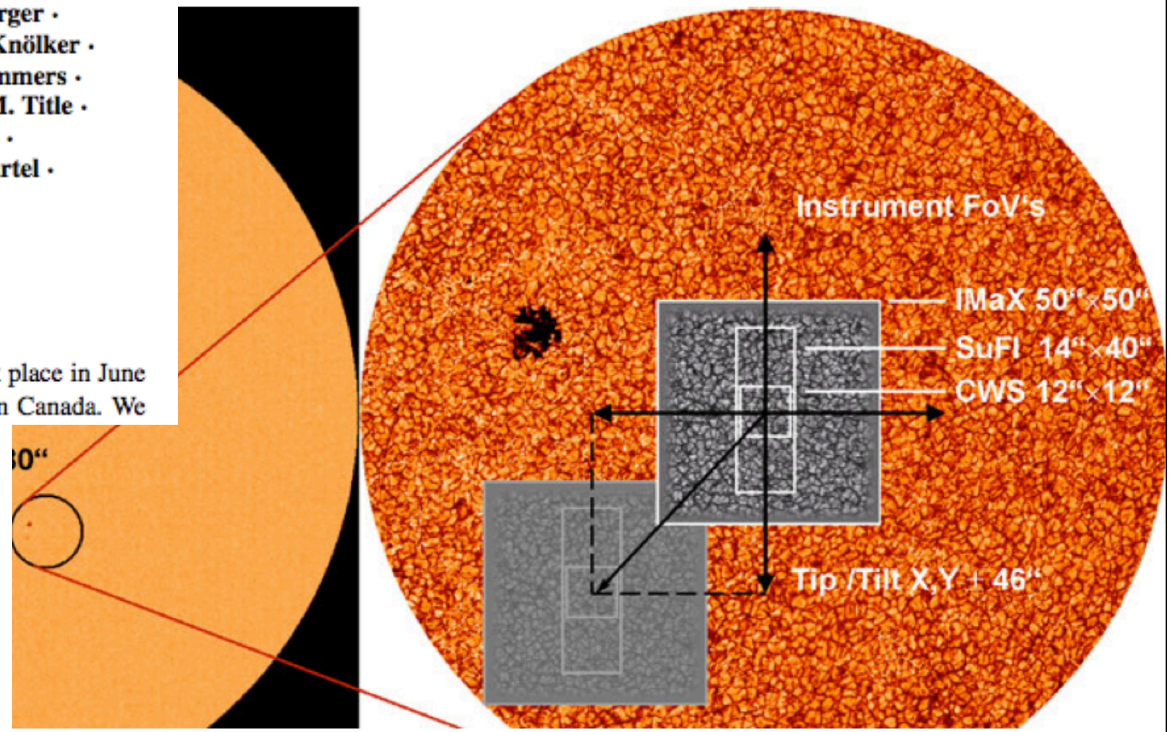
Abstract The first science flight of the balloon-borne *Sunrise* telescope took place in June 2009 from ESRANGE (near Kiruna/Sweden) to Somerset Island in northern Canada. We



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

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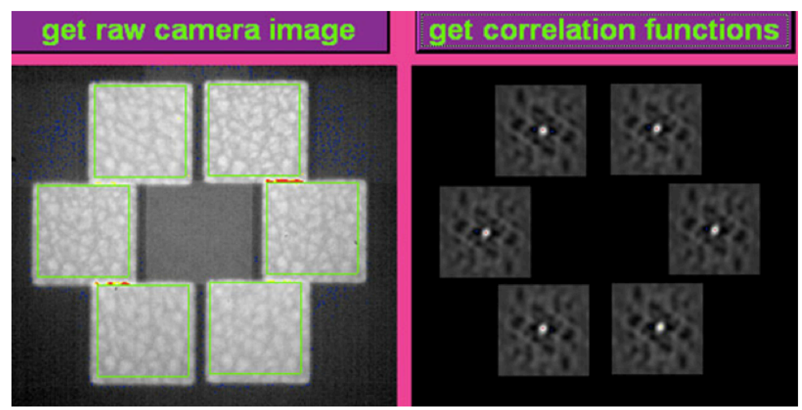

Diffraction-Limited Performance from 120,000 ft

	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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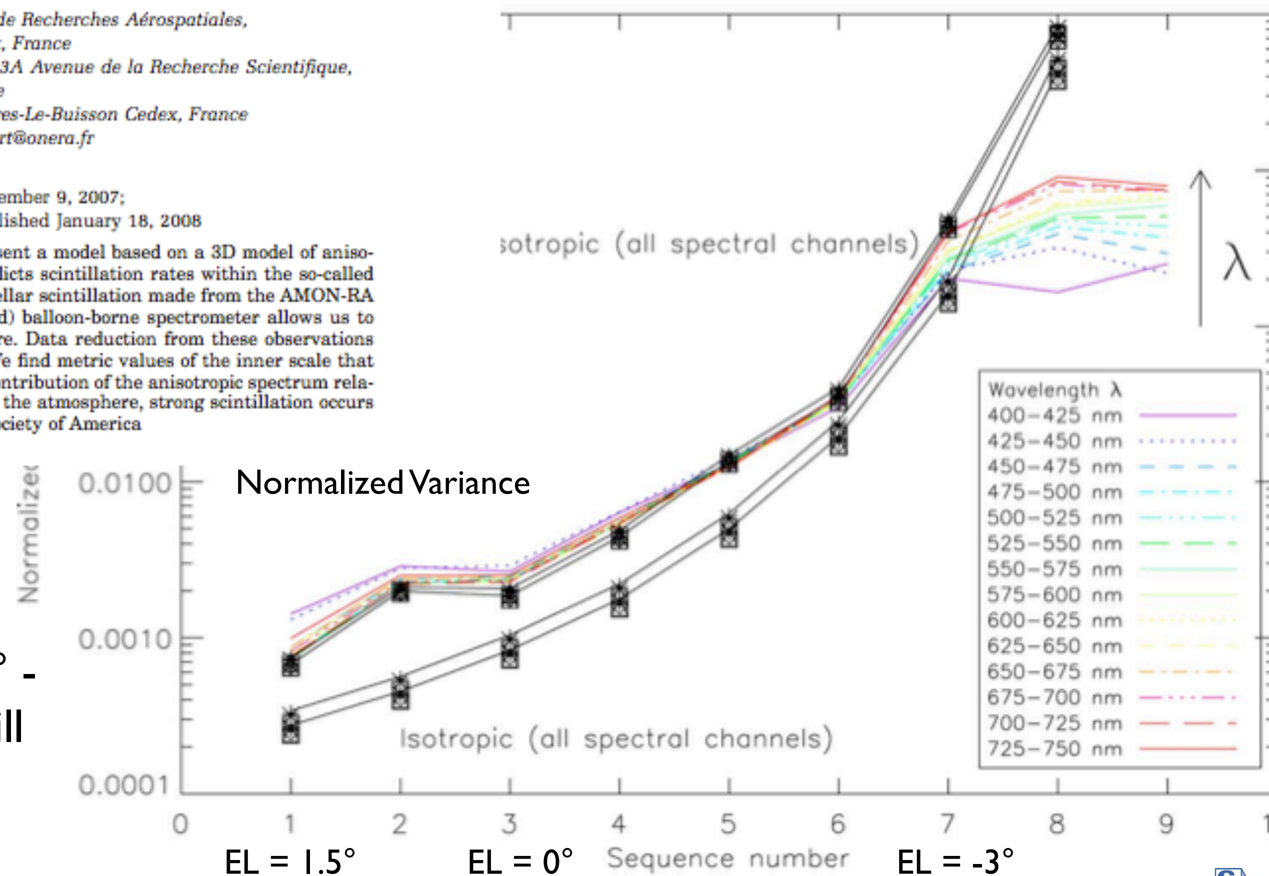
Scintillation effects are not negligible in the stratosphere. We present a model based on a 3D model of anisotropic and isotropic refractive index fluctuations spectra that predicts scintillation rates within the so-called small perturbation approximation. Atmospheric observations of stellar scintillation 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°!).



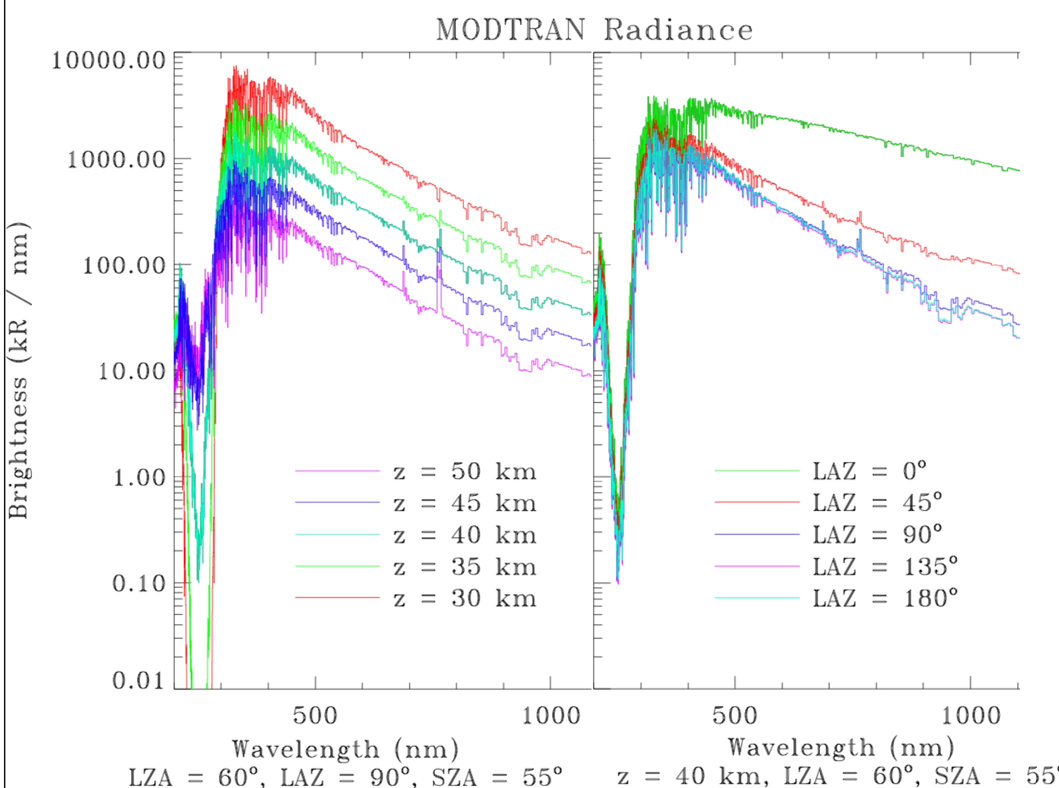
Short answer:

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

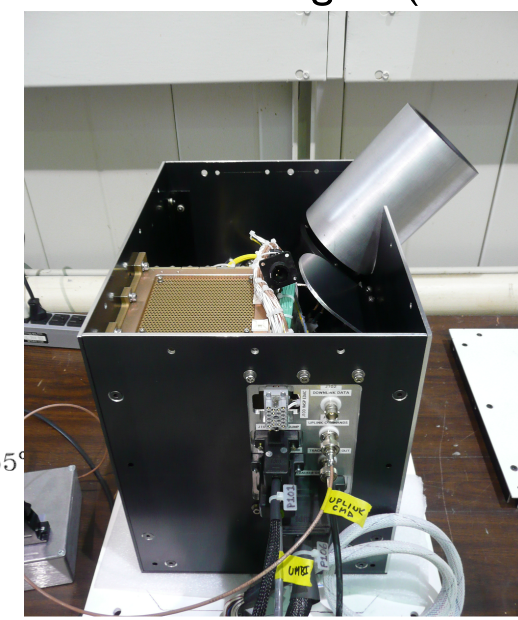
What is the Daytime Sky Background at 120,000 ft?

Sky Background model:

- Decreases with λ^{-4}
- Decreases by 2x for every 5km in z
- 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.

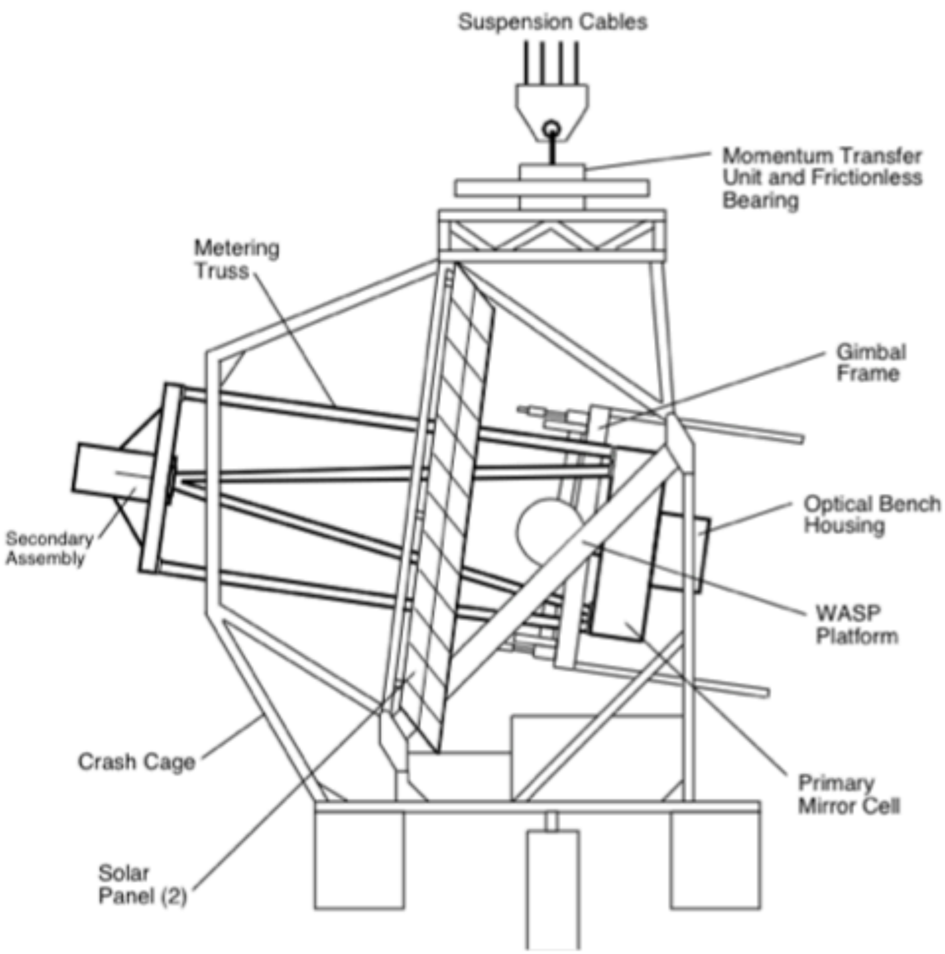
Summary of the near-space environment at 120,000 ft:

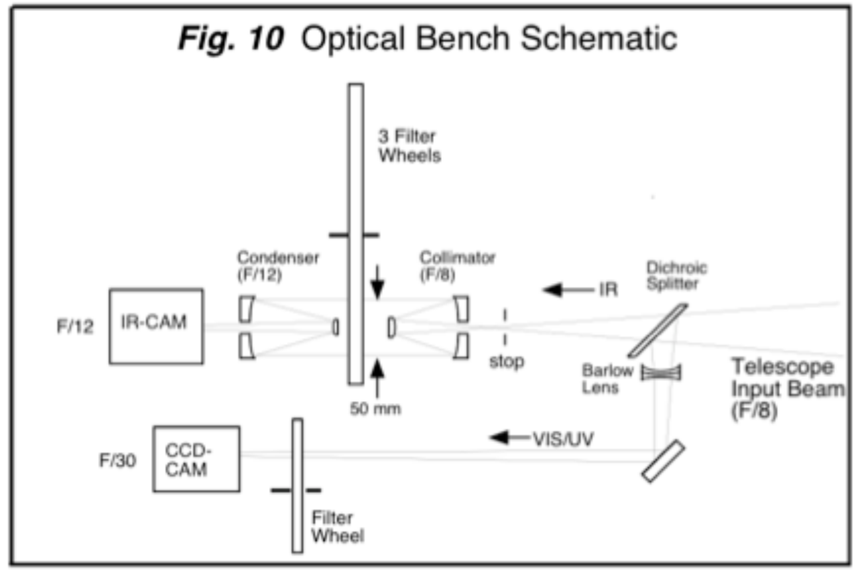
- ◇ Imaging: diffraction limited at $\lambda < 1\,\mu m$.
- ◇ Photometry: virtually no scintillation.
- ◇ Daytime: A problem at $\lambda < 1\,\mu m$.

Balloon-borne telescopes have an important niche at $\lambda < 1\,\mu m$. This is a regime that is only accessible to HST. It not covered by ground-based AO systems.

A Strawman Planetary Payload

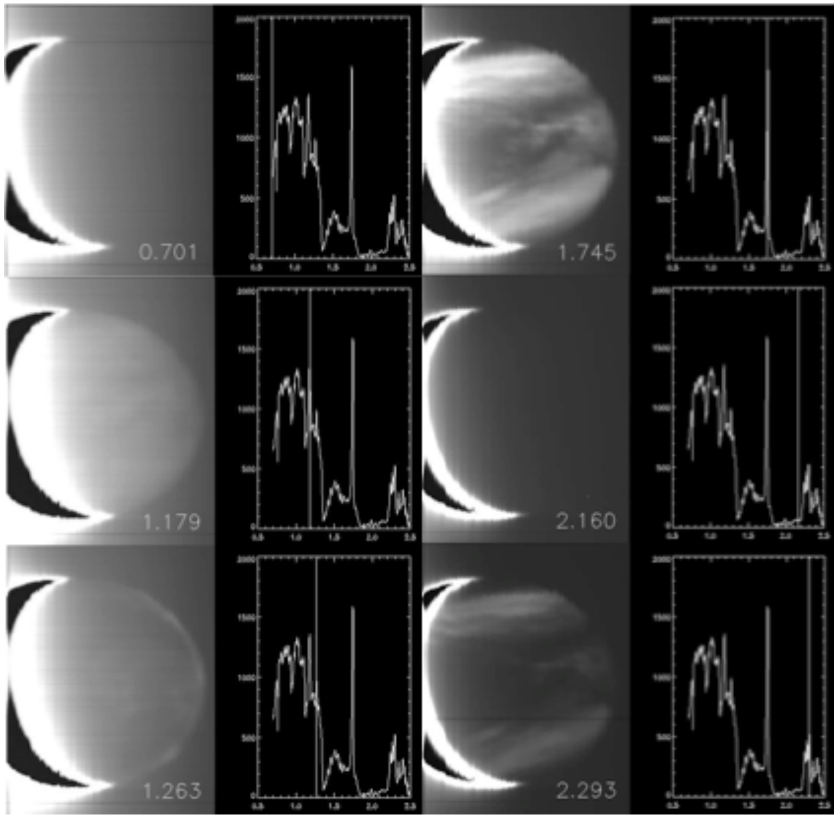
From Young et al. 2011, "Venus Stratoscope: A Balloon-Borne Campaign to Study Venus' Atmosphere and Surface," submitted to NASA/Planetary Astronomy.





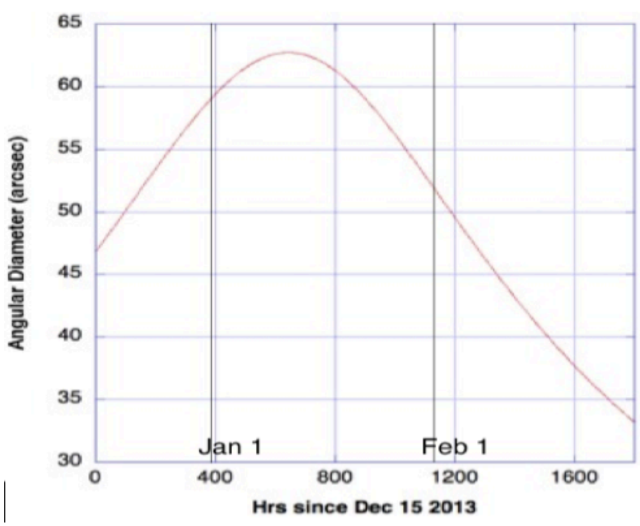
- One meter aperture - fits in WASP.
- Two cameras, IR (F/12) and CCD (F/30)
- Fast exposures (0.2 s), no Fine Steering Mirror. Over 90% of images should be diffraction limited (because of WASP).
- Estimated flight duration: 3 - 8 weeks. Estimated Cost (build, fly, recover): $3.85M

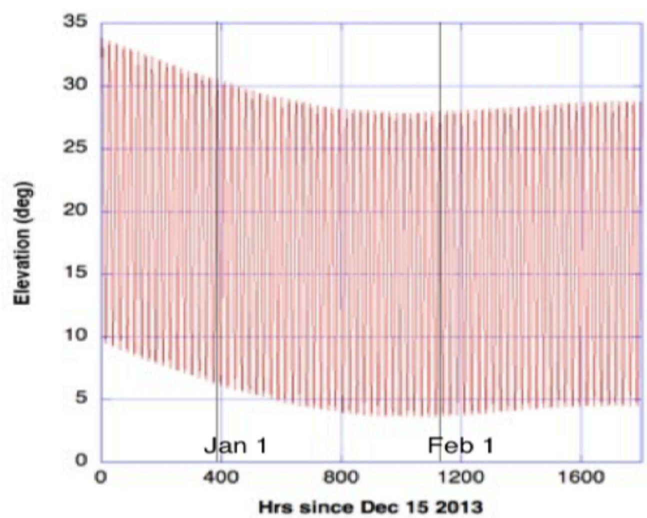
A Strawman Planetary Payload

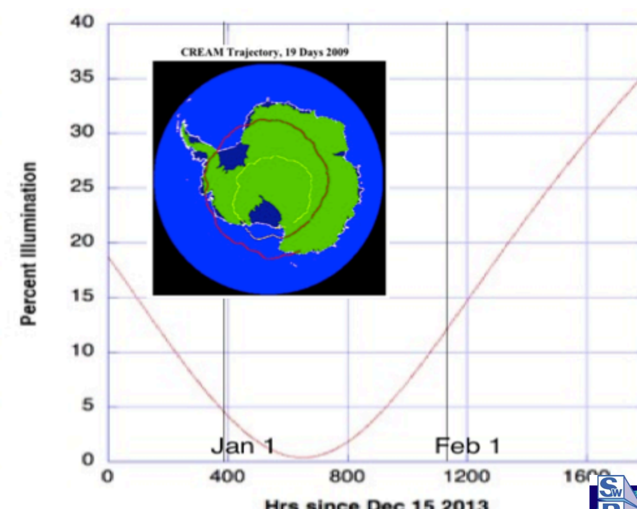


Venus from a stratospheric telescope:

- 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

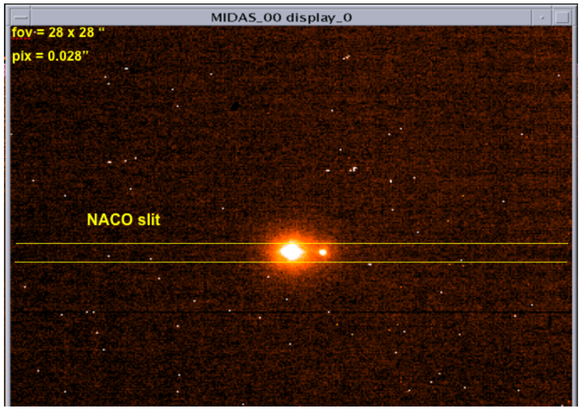


Fig 1. Spatially resolved spectroscopy of Pluto & Charon from the VLT/ NACO. Protopapa et al. 2010

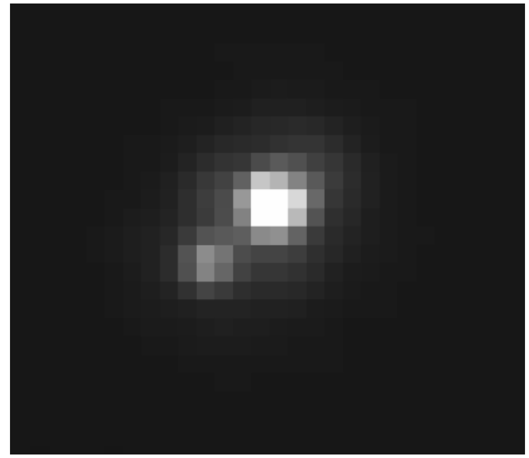


Fig 3. HST/HRC discovery of the binary centaur (42355) 2002 CR_{46} with 300 sec of on-target integration. Noll et al. 2006.

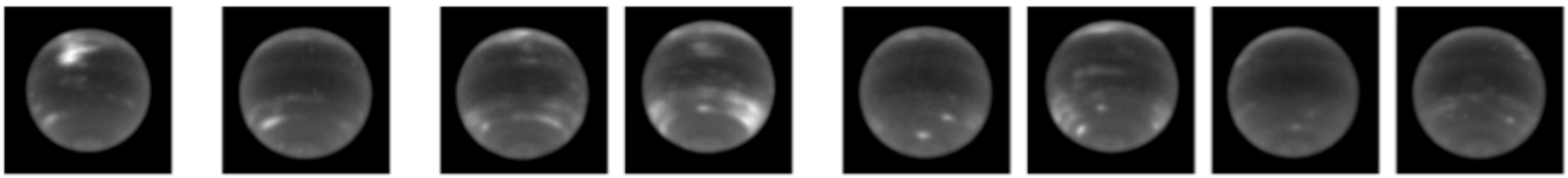


Fig. 2 Neptune (HST) in the 0.619 μm filter of WFPC2 in 1994, 1997, 2001-2002 and 2004-2007 (left to right).

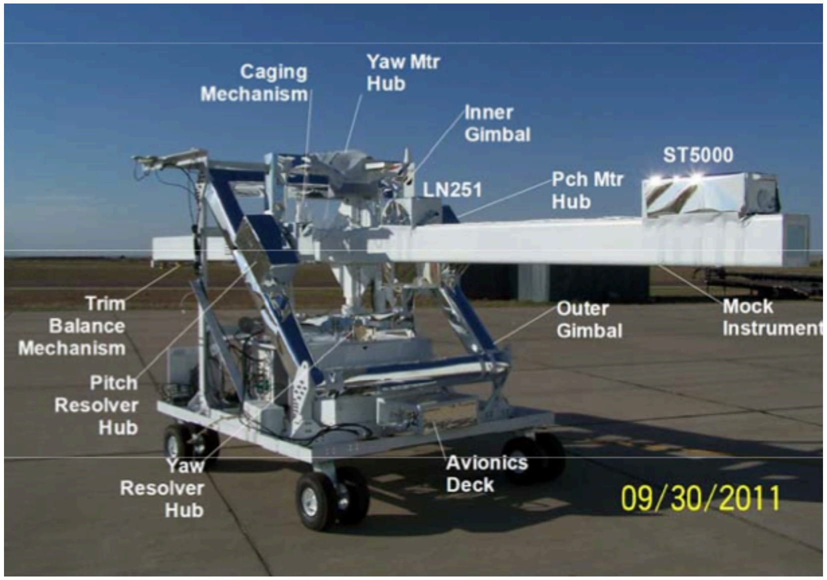
Some Broad Science Goals:

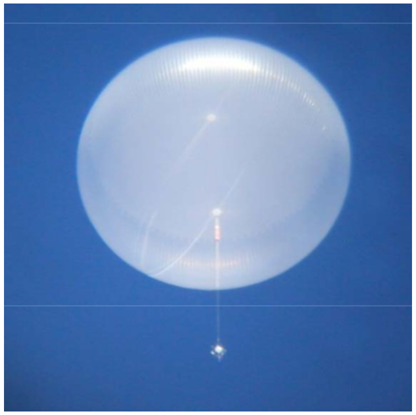
- Understanding basic weather on giant planets: long-term monitoring of the giant planets at wavelengths shortward of 1.0 μm.
- Clean PSFs: finding & observing faint objects, often next to bright objects. Goals include the understanding of formation scenarios (asteroids, centaurs, TNOs, satellites and 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.

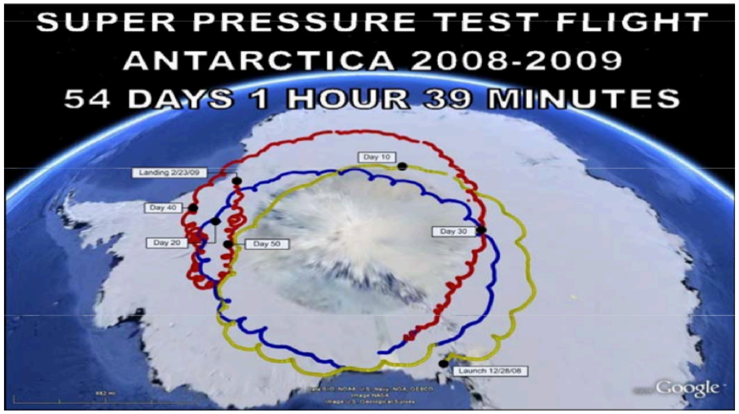
Balloon Science Opportunites: A simple 1-m telescope in the stratosphere has a 0.12" diffraction limit, outperforming every telescope shortward of 1 μm except for HST.

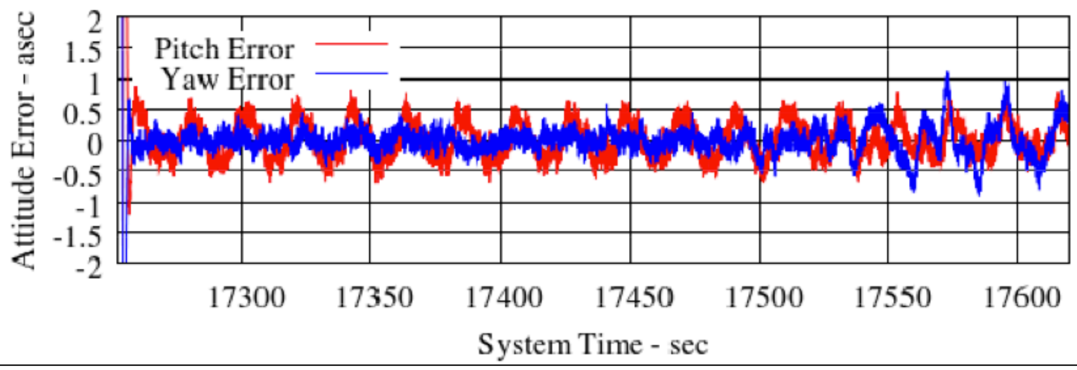
Recent Developments in NASA's Balloon Program

- Development of SUPER-PRESSURE balloons for extended day/night missions. NASA's 18 MCF balloon capable of lifting 5000 lb 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.









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

Parting Thoughts on Balloon-borne Telescopes

- ◇ Spatial performance: potentially better than HST.
- ◇ Time aloft: up to 100 days.
- ◇ Unique science capabilities: IR windows, space-like photometry, targets near the Sun, continuous monitoring of targets.
- ◇ Science per dollar: balloons not only achieve *unique* science, they are more cost-effective than large ground-based facilities.