Observations from Ground-Based, SOFIA and Balloon-Based Telescopes

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Comparison of 3 “Platforms” for Planetary Science

OVERVIEW OF TALK:

A comparison of advantages and shortcomings of ground-based telescopes, SOFIA, and stratospheric telescopes.

Ground-based

Let’s consider Keck telescopes, 10-m apertures at 14,000 ft with adaptive optics capabilities.

SOFIA

A 2.5-m aperture operating between 39,000 and 45,000 ft.

Stratospheric Balloons

Let’s consider 1-m to 2-m apertures at 120,000 ft.

Summary of GROUND-BASED Characteristics

Spatial Resolution

With adaptive optics: 0.05” at H-J-K bands. Adaptive optics not effective below 1 μm, but natural seeing can be as good as 0.5” in the visible.

Telluric Absorption

Significant opacity due to telluric water, CO, CO_2, CH_4 and other constituents.

Access

Nightly observing, but subject to weather. Daytime usually prohibited (IRTF an exception). NASA/Keck planetary allocation is ~5 nights per semester.

Cost

An amortized night on Keck = ~$48K

Summary of SOFIA Characteristics

Spatial Resolution

Current performance: ~4” at 0.6 μm.
Eventual spec: 1.6” at 0.6 μm.

Telluric Absorption

Virtually NO telluric water absorption, but CO, CO_2, CH_4 are still factors.

Access

Eventual goal: 960 hr per year (6 hr at 41,000 per flight, 40 PI/GI teams/yr).
Can be deployed from any airport that supports 747s. Not subject to clouds.

Cost

$78M per year.

Summary of BALLOON Characteristics

Spatial Resolution

Diffraction limited. At 0.5 μm, a one meter telescope has 0.12” resolution; a 2-m telescope has 0.06” resolution.

Telluric Absorption

Above 99.5% of the atmosphere. Virtually no telluric absorptions from 0.3 to 5 μm (even 4.3 μm is workable).

Access

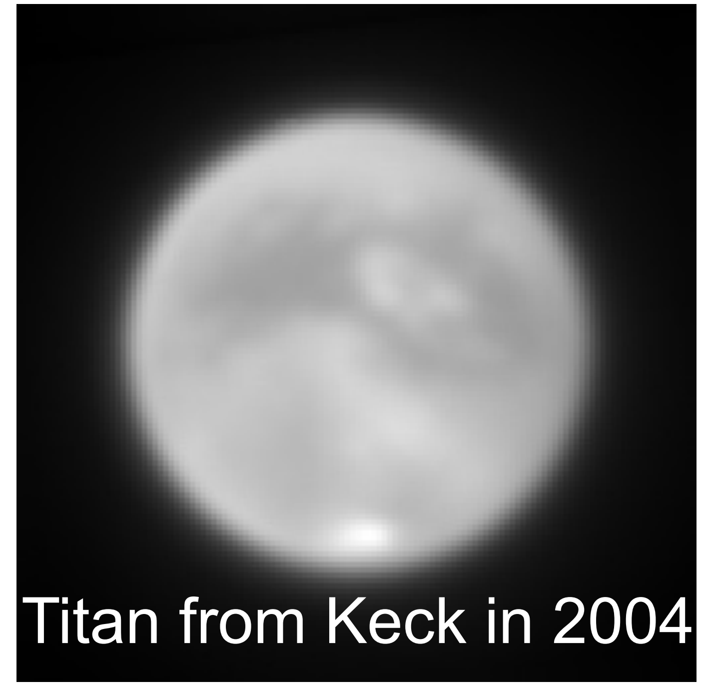
Not subject to clouds. Flight durations up to 40 days (100 days being considered). Launches are affected by weather.

Cost

Launches from $100K to $1M. Payloads at the $5M+ level (typical in APRA).

SPATIAL RESOLUTION in DETAIL

Atmospheric seeing at 120,000 ft is insignificant (evidence: the SUNRISE mission's wavefront sensor). Balloon-borne telescopes can operate at the diffraction limit, *even in the visible*.


Titan from Keck in 2004

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

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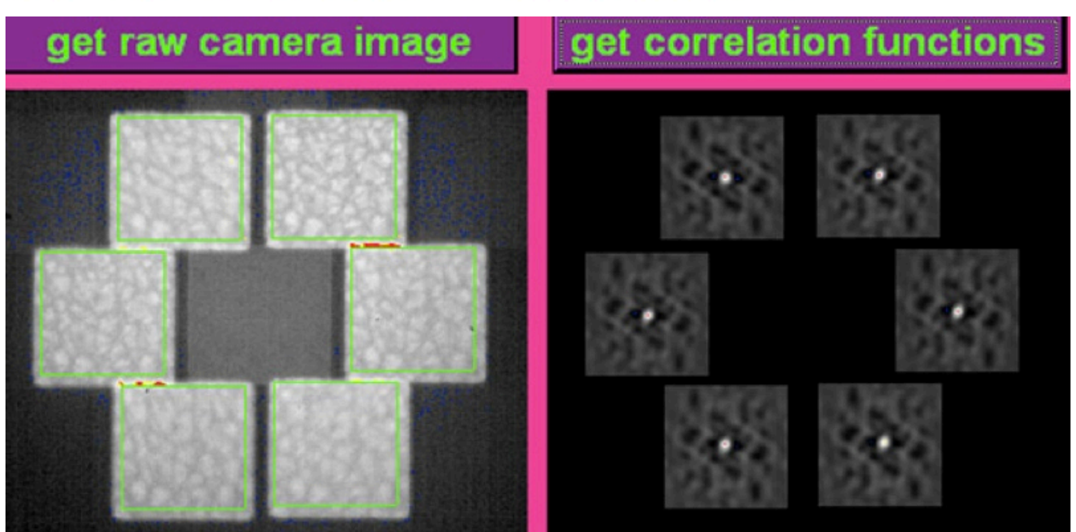
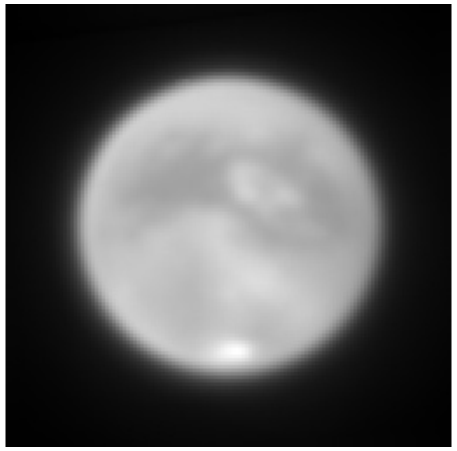


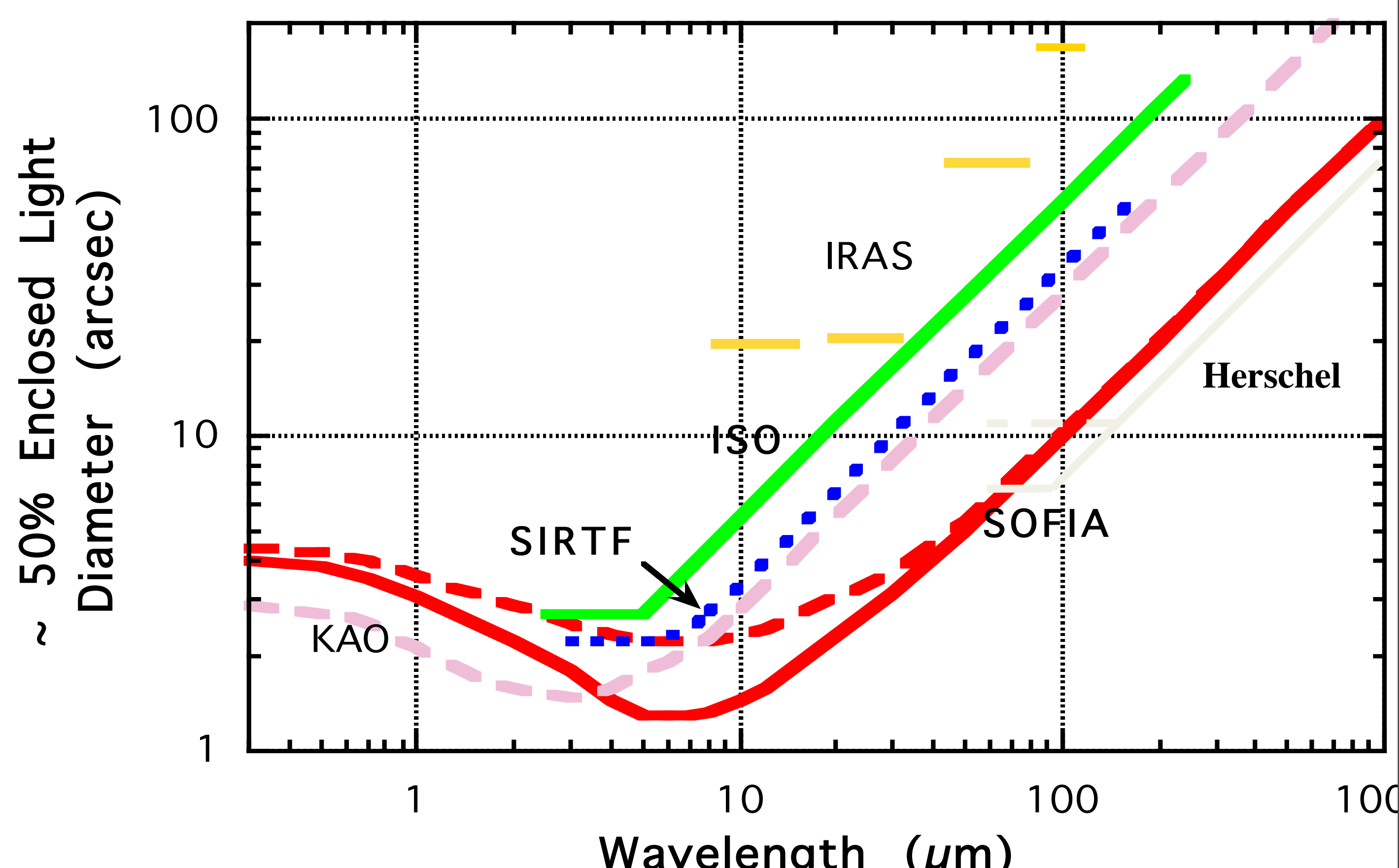
Adaptive optics systems on the Keck, Subaru, Gemini, VLT (and other) telescopes work well in IR wavelengths longer than 1.2 μm, with Strehl ratios up to 60 - 70% in K-band. However, these AO systems do not work in visible wavelengths.

SPATIAL RESOLUTION in DETAIL



From SOFIA, the spatial resolution is several arcseconds. Titan (at left) subtends 1” - it would not be resolved by SOFIA.

Angular Resolution



In contrast, a one-meter balloon-borne telescope can resolve Titan into 75 resolution elements.

Conclusions:

1) 1-m balloon-borne telescopes obtain roughly 25x more elements than KECK in visible wavelengths (λ < 1.0 μm).
2) 1-m balloon-borne telescopes obtain more than 1000x more areal elements than SOFIA.
3) 1-m balloon-borne telescopes cannot compete with Keck at λ > 1.2 μm (unless you consider 4-m telescopes and larger).

Space-based vs. Ground-based telescopes with Adaptive Optics (AO)[1]

Why is Hubble so critical, when we now have much larger ground-based telescopes?

- Ground-based adaptive optics today only works at infrared wavelengths.
- Achieving Hubble-quality images at optical wavelengths is more than 10 years away and not even the focus of current AO development for astronomy. Projections indicate that the optical images obtained from the largest telescopes in 2015 will have an image quality no better than Hubble's before the optics corrected the spherical aberration of the primary mirror.
- Hubble is sensitive to all wavelengths from the ultraviolet to the near infrared. Many of these wavelengths are blocked by the atmosphere and inaccessible from Earth.
- Despite advances in image quality, the sensitivity of groundbased telescopes is limited by the enormously greater foreground radiation from the Earth's atmosphere. On a moonless night, the sky at 0.7 microns is eight times brighter from the top of Mauna Kea in Hawaii than it is from Hubble. At 1.5 microns it is 600 times brighter.
- Hubble images are stable. Even with AO, the atmosphere causes quality to vary in images taken with ground-based telescopes (with position and time), making precise measurements extremely difficult. Hubble stability is the main reason it is used to detect the atmospheres of extra-solar planets such as Osiris.
- Observations with AO require relatively bright guide stars to correct for atmospheric turbulence. This currently limits applications to less than 1% of the sky. Even in the observable areas, AO image quality degrades rapidly with distance from the guide star. At optical wavelengths, AO would correct fields of view 100 to 1000 times smaller than Hubble's.

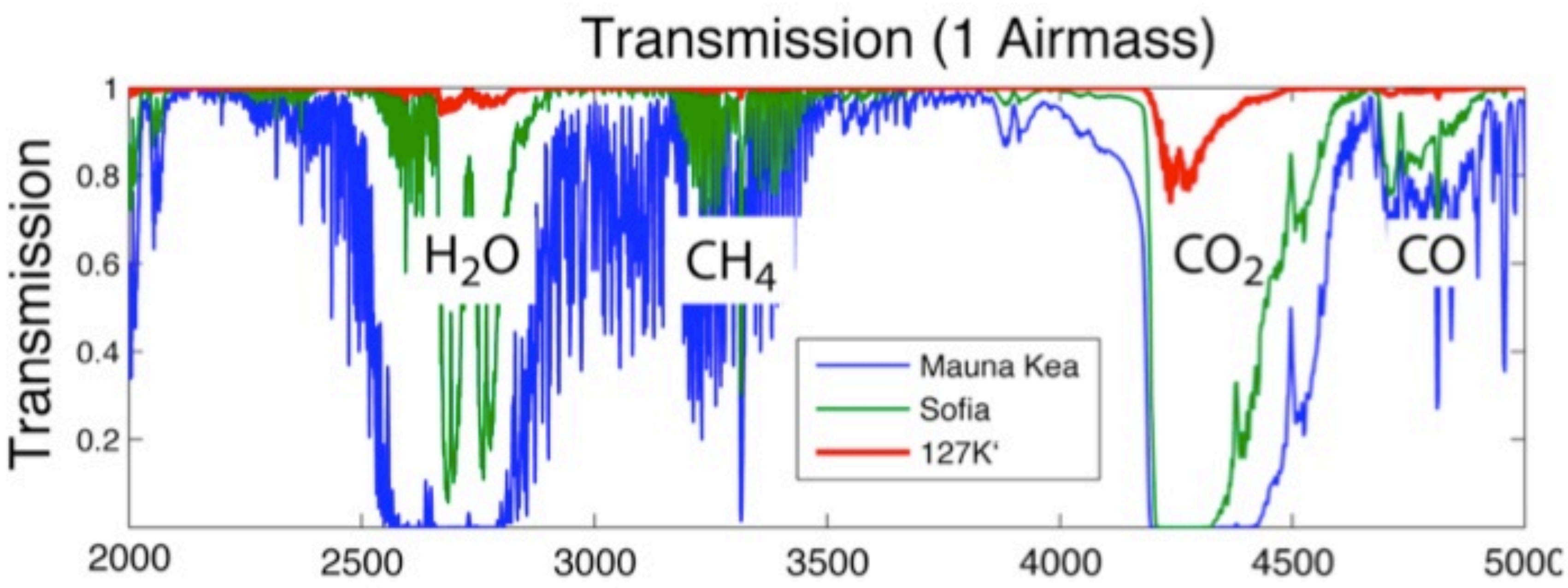
[1] **A summary prepared by the scientific staff of the Space Telescope Science Institute, which is Operated by the Association of Universities for Research in Astronomy (AURA), Inc., under NASA contract NAS5-26555. Please direct questions or comments to Henry Ferguson (ferguson@stsci.edu).**

NOTE:
Balloon-borne observatories will be one of the ONLY ways to provide diffraction-limited resolution comparable to that of HST in visible wavelengths.

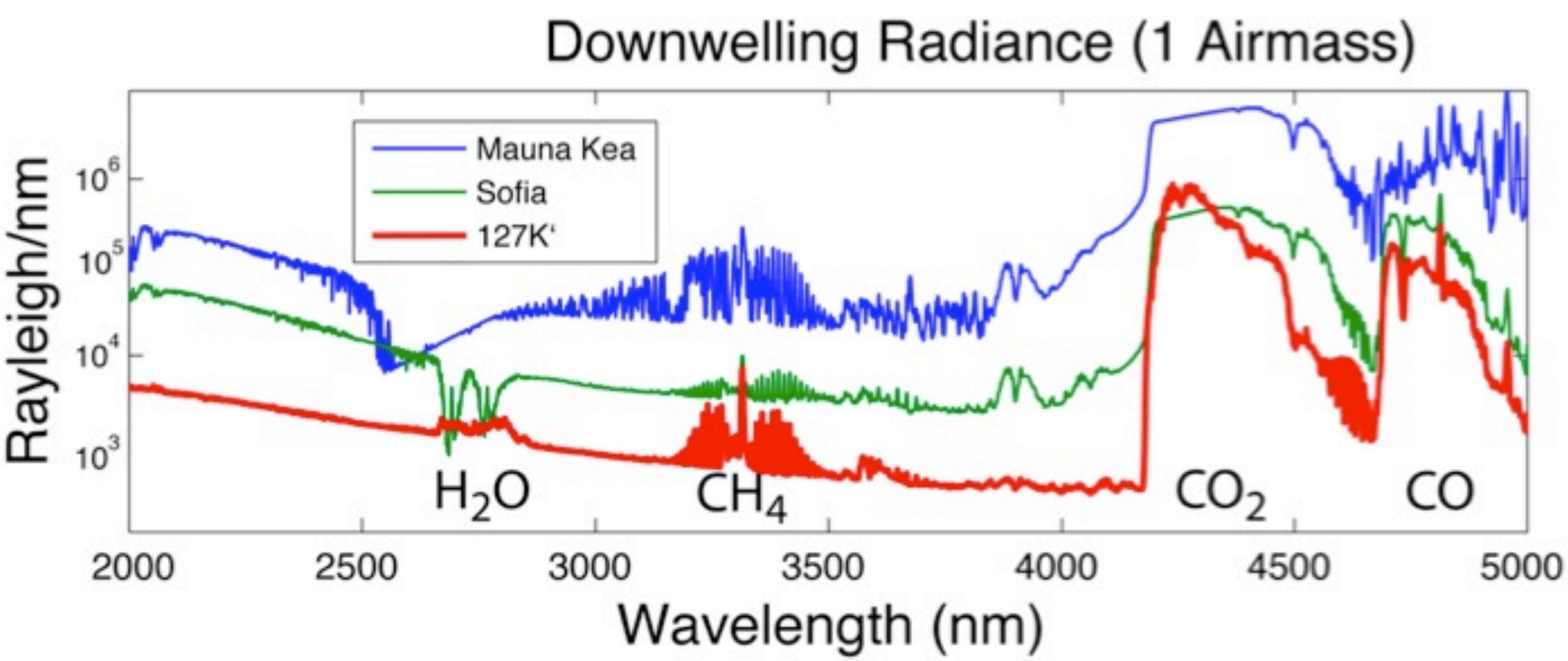
For that reason, the justification of balloon-borne resolutions (given AO performance in H-K bands) is the *same* as the case for HST (left).

ATMOSPHERIC OPACITY

Balloon-borne observatories have a strong advantage over SOFIA and ground-based observatories with respect to telluric transmission and infrared backgrounds. SOFIA sees 15x more atmosphere overhead than a balloon-borne observatory at 120,000 ft.



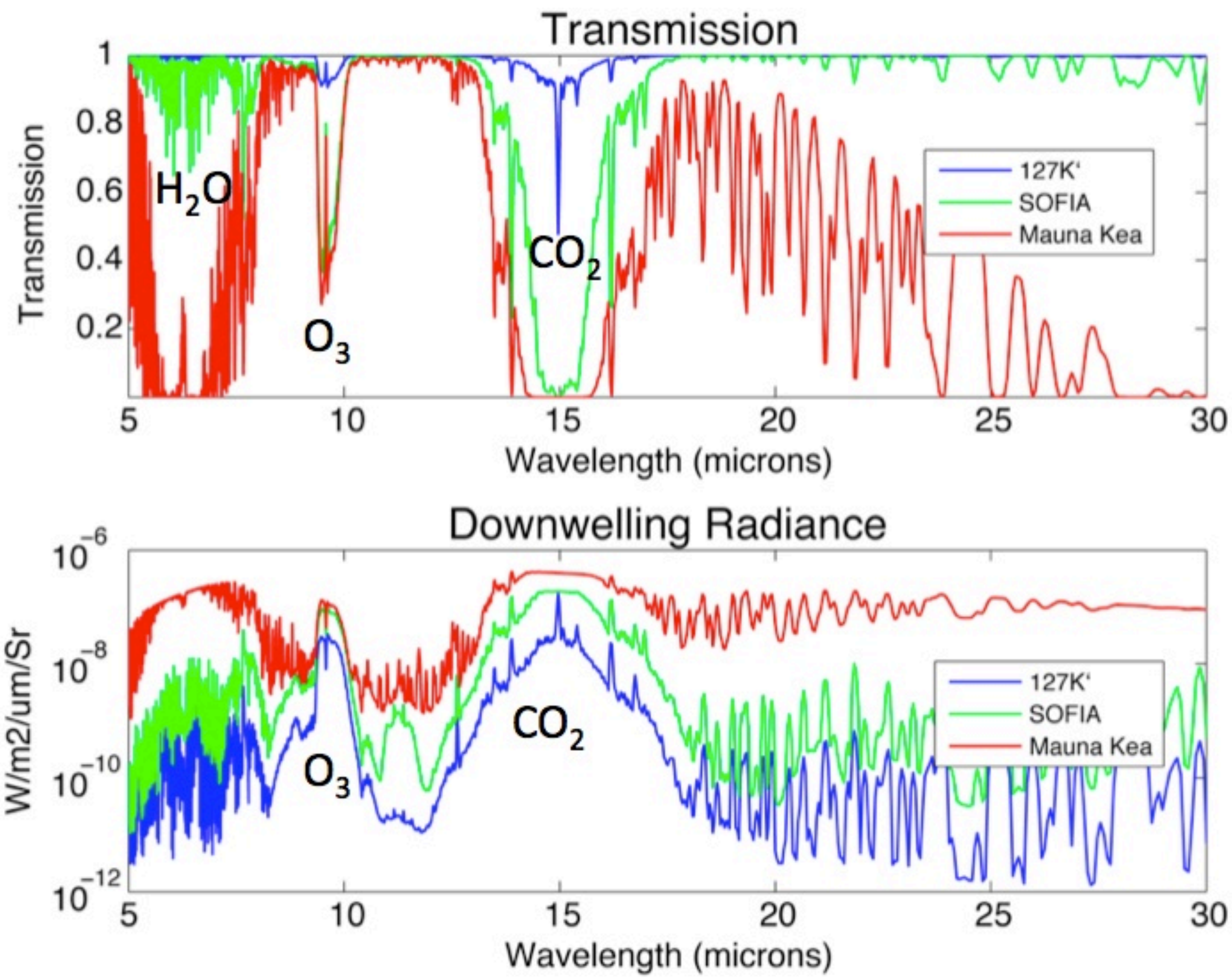
The telluric methane and water lines are almost completely absent and transmission exceeds 70% within the CO_2 band.



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

ATMOSPHERIC OPACITY (THERMAL IR)

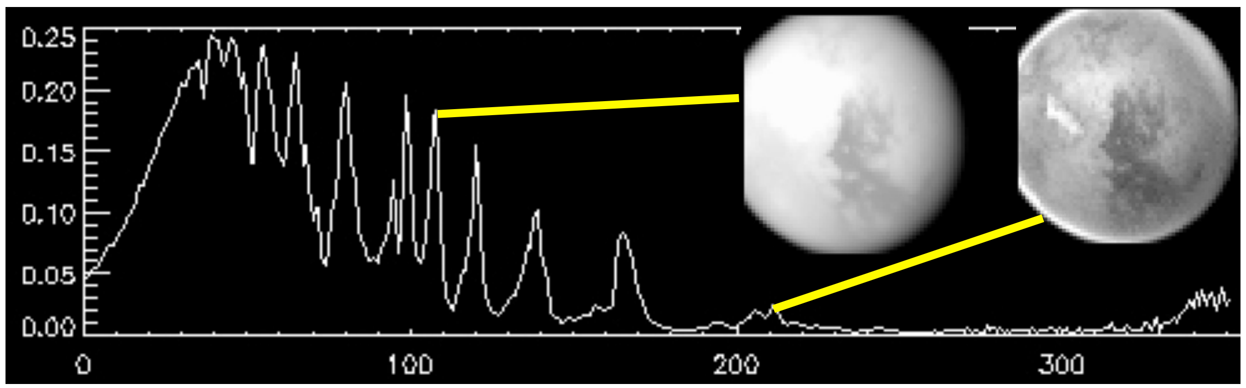
The balloon-borne advantage extends to the thermal IR as well. Even the strong CO_2 features are usable from 120,000 ft. The IR background is much less too.



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

SPECIFIC COMPARISONS: Cassini/Methane on Titan

On TITAN, one of the pressing questions is the methane cycle: how does methane move between the surface and the atmosphere, what is methane's role in the weather of Titan, what is its role in the chemistry of Titan's atmosphere, and what is the methane resupply mechanism (given the 10 - 20 MY lifespan of CH_4 due to photolysis).



The **VIMS** instrument on Cassini provides image cubes (0.3 - 5 μm), but the visible part of the spectra do not have sufficient SNR to map the presence of methane.

SOFIA cannot resolve Titan's disk and is not useful for mapping.

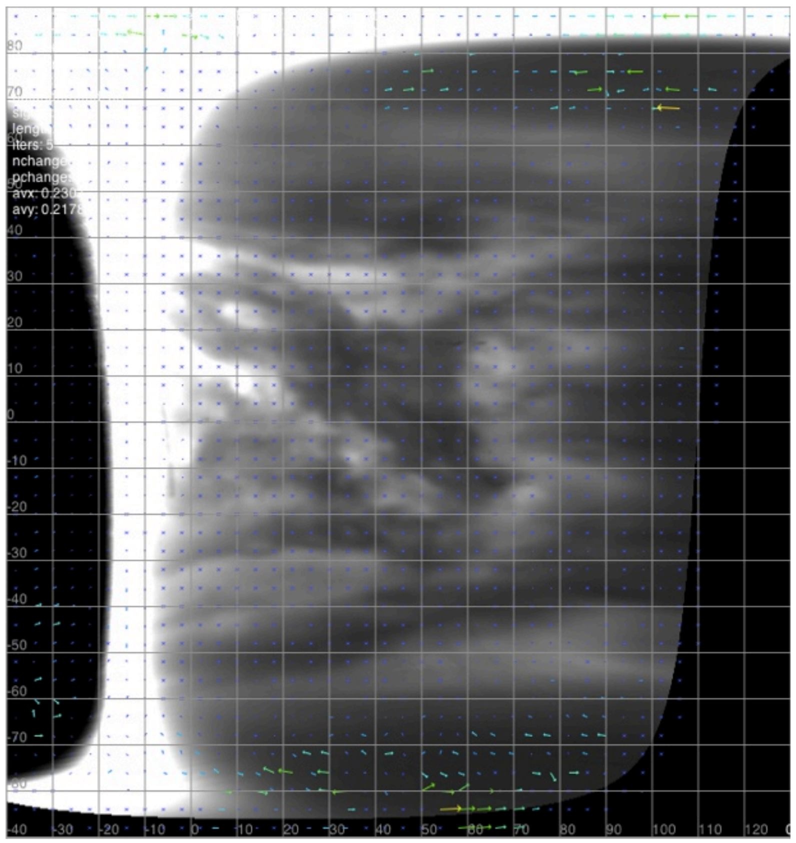
Keck has several instruments (NIRSPEC, NIRC2, OSIRIS) that have been used successfully to obtain spectra of Titan from 1.2 to 2.6 μm.

Balloons uniquely fill a key role that HST/STIS used to fill: spatially resolved spectra over the 0.5 - 1 μm range. This range complements the H-J-K bands with methane bands at 0.62 and 0.89 μm. The shorter bands (a) probe CH_4 abundances *below* Titan's tropopause and (b) are diagnostic for the opacity due to haze when combined with VIMS data at the 1.7 and 2.3 μm CH_4 bands.

SPECIFIC COMPARISONS: Venus Express/Wind Fields

The super-rotation on Venus has been a long-standing question: what is the circulation on Venus that gives rise to winds that are 60x faster than the planet's solid-body rotation?

Both Venus Express and VCO missions are dedicated to understanding Venus' circulation by tracking clouds in various CO_2 windows.



Ground-based observations play a role: although **Keck** does not observe Venus during inferior conjunction (too close to the Sun), **IRTF** allows us to derive cloud velocities with error bars *smaller* than those from VEX/VIRTIS observations.

SOFIA does not currently look at Venus during daytime, but the heterodyne GREAT instrument could potentially be adapted to measure wind speeds directly from altitudes near 100 km.

Balloons are particularly well suited to observe Venus during upcoming inferior conjunctions: 40+ days of *continuous* cloud tracking observations with resolutions 4x better than the IRTF.

SPECIFIC COMPARISONS: New Horizons/TNO Discovery

The New Horizons mission will fly by Pluto in 2015 and continue to a TNO that has yet to be identified (but must be accessible with a delta-V of 100 m/sec or less). There has been a large coordinated ground-based campaign to find the 26-mag candidate, with best results coming from wide-field ground-based cameras during good seeing conditions. The crowded target field is in the galactic plane.

We think that a one-meter balloon - with a large focal plane array - could outperform the upcoming HSC on Subaru, given the 0.1" resolution of the balloon-borne telescope.

Exercise for the reader: a detailed SNR comparison between a ground-based 8- or 10-m telescope (0.5" seeing) and a stratospheric 1- or 2-m telescope with 0.1" or 0.05" seeing.