

Optical Turbulence in the Antarctic Atmosphere

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ABSTRACT

Turbulence in the earth's atmosphere severely limits the resolution and sensitivity of astronomical observations. The vertical distribution of turbulence in the atmosphere has a profound effect on the residuals after correction by an active instrument such as adaptive optics or a fringe tracking interferometer. It has already been shown that the South Pole has turbulence profiles unlike those at any other site, dominated by ground layer turbulence, with low free air seeing. This paper examines the meteorology, climatology and atmospheric physics that produces these conditions. Combining meteorological observations at remote sites with models of atmospheric turbulence allows quantitative extrapolation to the likely conditions at sites now under development and consideration that may provide the ultimate ground based site for near and mid-infrared interferometry. The high plateau sites in Antarctica will likely enable complete sky coverage for adaptive optics and interferometry in the near infrared with natural guide stars.

Keywords: Turbulence, Seeing, Adaptive Optics, Interferometry, Antarctica

1. INTRODUCTION

Properties of the atmosphere are the limit for ground based astronomy. Transparency and sky brightness limit the sensitivity of a telescope, and atmospheric turbulence, "seeing", limits resolution. For seeing limited observations, the natural seeing determines the image size, which is of importance not only for resolution, but also for sensitivity as the light from a point source is concentrated into a smaller area, thus suffering less from noise from the contaminating background. For this reason, astronomers have been seeking to deploy telescopes at high altitude sites with stable air for several decades. With the advent of adaptive optics and interferometry, the loss of resolution can be recovered by measuring and tracking the aberrations induced by the atmospheric turbulence. Although it is widely perceived that these techniques can correct for seeing, the seeing enters into the difficulty of the problem in more ways than the image area. The temporal and angular dimensions of coherence of the atmosphere, in addition to the spatial, degrade adaptive optics and interferometry performance. Therefore, these techniques are even more sensitive to degradation by atmospheric turbulence than uncompensated imaging.

It has been recognized for some time that the Antarctic offers the potential for not only exquisitely clear and dark skies, but also for the lowest level of turbulence, with its lowered diurnal variation, high altitude, and remarkably flat topography.¹ The combination of superb seeing, low background and high transmission in the thermal infrared allows high levels of performance with an interferometer for the detection and study of extrasolar planets.²⁻⁷

2. TURBULENCE IN THE ATMOSPHERE

In general, turbulence is very poorly understood. The basic model of Kolmogorov turbulence, however, is practically very useful. In this model, turbulent eddies are injected at some large "outer" scale, and break into smaller eddies in a self-similar cascade. This model predicts a power law distribution of turbulent power that is in fact observed. The basic model of the turbulence that concerns astronomers is similar, see Figure 1.

This model of turbulence addresses only the mechanical component of the turbulence. Mechanical turbulence results in optical turbulence as a result of the incomplete mixing of air of varying temperature, and therefore density, as in Figure 2. As the refractive index of air changes with density, wavefronts passing through this inhomogeneous medium are delayed by variable amounts depending on the turbulence.

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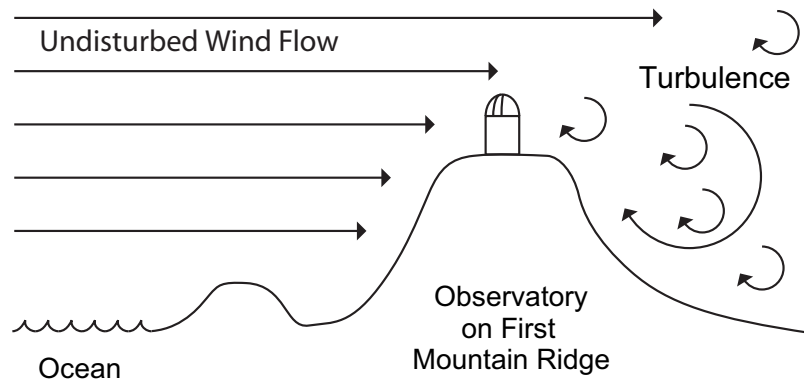


Figure 1. The conventional wisdom of turbulence generation in the wake of obstacles, adapted from Quirrenbach 2000.⁸ Observatories are frequently located on the first mountain ridge near the coast (or on mountains on islands), with prevailing winds from the ocean to avoid this type of turbulence.

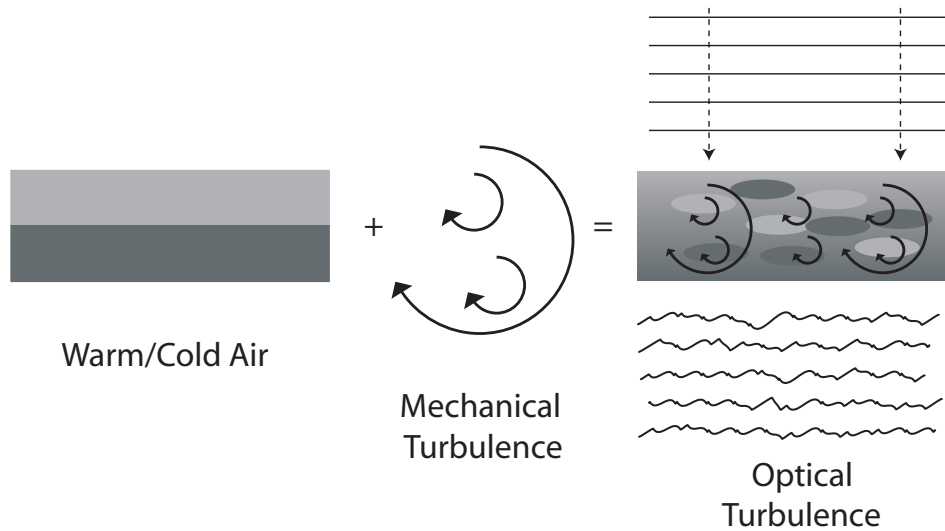


Figure 2. The generation of optical turbulence. Incomplete mixing of warm and cold air results in density inhomogeneities that modulate the delay to a wavefront.

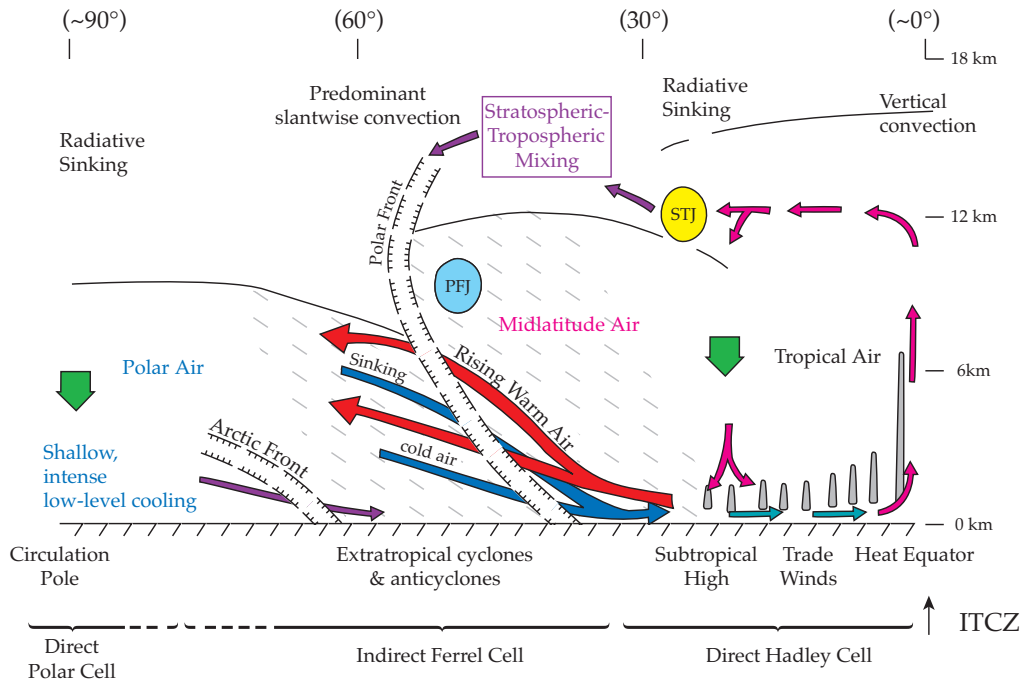


Figure 3. Global circulation and tropopause patterns, adapted from Linacre & Geerts.¹⁰

3. THE ANTARCTIC ATMOSPHERE

As the optical effect of the turbulence results from the combination of mechanical turbulence with air temperature it is worth examining the processes that generate these. The Palmen-Newton model of the general circulation of the atmosphere (see Figure 3) illustrates several of the basic processes. The heating of the sun drives convective turnover on large scales in the tropics and mid latitudes. This turnover in turn drives strong winds such as the trade winds at low altitudes and the jetstreams at high altitudes. Variations in local topography, such as mountains, oceans and deserts, result in inhomogeneous heating that constantly produces synoptic weather patterns with large scale inhomogeneous air masses. Of particular concern for astronomy are places where the combination of wind shear and temperature inhomogeneities results in strong turbulence, such as the jet stream and fronts between hot and cold air masses. Periodically, the strong turbulence produced at these interfaces degrades the seeing at mid-latitude sites to very poor levels.

By comparison, the atmosphere over Antarctica is remarkably simple. The sole dominant process is the cooling and sinking of air over the plateau, resulting in katabatic winds. As the Antarctic plateau is nearly uniformly flat and white as a result of the ice cap, there is very little potential to drive convection on large scales. In the wintertime, the atmosphere becomes very nearly adiabatic.⁹ In an adiabatic atmosphere, even the injection of mechanical turbulence will not result in optical turbulence, as the density of the air remains uniform at all altitudes.

4. SOUTH POLE SEEING

On the basis of these considerations, the seeing at Antarctic plateau sites should be superior to any mid-latitude sites, as has been recognized previously.^{1,11} Comprehensive site testing at the South Pole has characterized not only seeing, but background and transparency at a range of wavelengths.¹²⁻¹⁹ However, the seeing at the South Pole was found to be relatively poor, with median seeing of 1.7" at 0.5 μm .

The vertical distribution of the turbulence was extensively studied with balloon measurements²⁰⁻²² and SODAR¹² and found to be confined to a low altitude layer, as in Figure 4. The mechanism that produces this

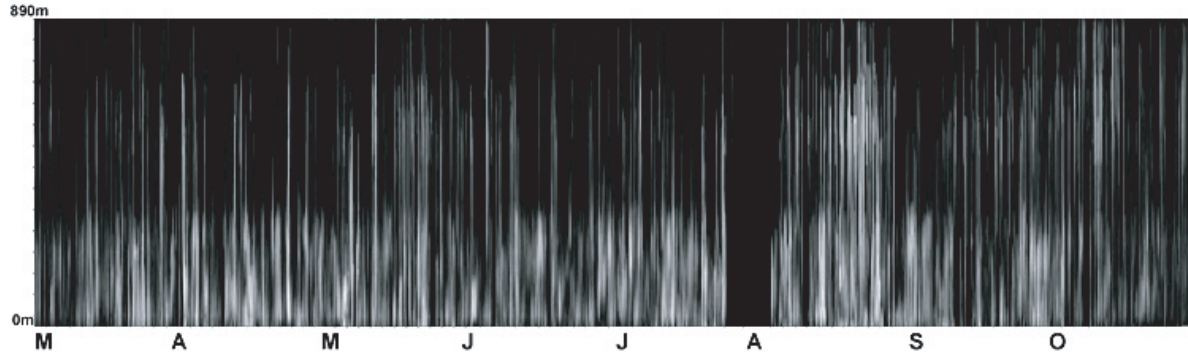


Figure 4. One year of SODAR profiles of the boundary layer turbulence at the South Pole.¹² The strong turbulence arising in the inverted lower 200 meters is almost always present. A secondary peak at 600 meters occurs particularly frequently in late March and August, near sunrise and sunset when the south pole frequently experiences disturbed weather. The implications of this layer for adaptive optics and interferometry are summarized in Lloyd et. al.³

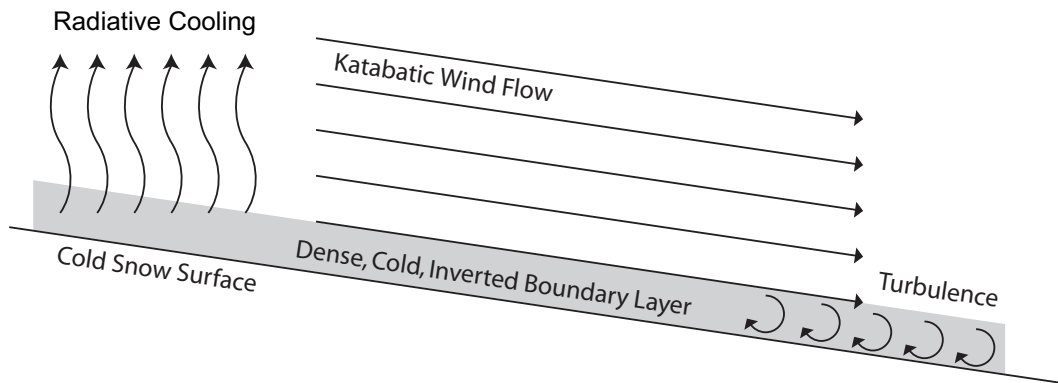


Figure 5. Generation of turbulence in the boundary layer by katabatic wind across the strong wintertime temperature inversion.

turbulence is illustrated in Figure 5. The radiative cooling of the ice to space results in a strong thermal inversion in the lower 200 meters of the atmosphere. As the South Pole is significantly downhill from the high point of the plateau, it experiences a constant katabatic wind of several meters per second in the wintertime (see Figure 8). The sloshing of the cold boundary layer under the action of this wind produces the optical turbulence that results in the relatively poor seeing. It is worth noting, however, that although this seeing is poor for the purposes of image formation, it is less degrading to adaptive optics and interferometry applications due to larger coherence times and isoplanatic angles than comparable seeing at a mid-latitude site.³ This component of the turbulence, however, is likely to be absent at the low wind sites on the high plateau. The free atmosphere turbulence measured at the South Pole indicates that under such conditions, exquisite seeing might indeed prevail.

5. IMPLICATIONS FOR ADAPTIVE OPTICS AND INTERFEROMETRY

The sensitivity limit for phase referenced observations in adaptive optics and interferometry is the requirement of a sufficiently bright guide star. The appropriate parameter to characterize a site in terms of phase referencing sensitivity is the “coherence volume” (see Figure 6). There must be sufficient photons within a coherence volume

to make a measurement of the wavefront phase. In the case in which the guide star is the science object, this requirement severely limits the applicability of adaptive optics and interferometry only to bright objects.

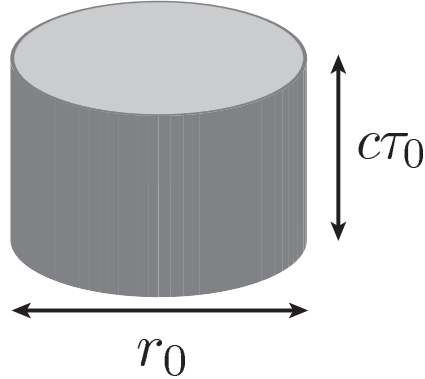


Figure 6. Representation of coherence volume. The coherence volume $\sim r_0^2 c\tau_0$ limits the sensitivity of coherent astronomy. In principle, adaptive optics and interferometry requires at least one photon per coherence volume. In practice many more are typically required due to instrumental inefficiencies. The coherence volume is a convenient parameter to characterize the potential sensitivity of a site for adaptive optics and interferometry.

Due to the severe limitations imposed by the required guide star brightness, astronomers have turned to techniques such as laser guide stars,^{23,24} or phase referenced observations whereby a science object separated from the guide star by some angle θ is observed using the correction obtained from the brighter guide star. In this case, the angular coherence parameter of the atmosphere, θ_0 , enters into the accessible astronomical observational parameter space. For the purposes of this discussion, we can define a “coherence etendue” (see Figure 7) as the product $r_0^2 c\tau_0 \theta_0^2$. This parameter then describes the transport of “coherence”, in the sense of the number of photons that remain mutually coherent with respect to each other, through the atmosphere.

Approximately, the coherence time τ_0 is limited by the advection of the turbulence over the aperture of the telescope by some wind speed \bar{v} (Taylor’s frozen flow approximation) so

$$\tau_0 \sim \frac{r_0}{\bar{v}}. \quad (1)$$

Although in reality, the turbulence is three dimensional, the turbulence is frequently approximated by a single phase screen at an effective turbulence height \bar{h} conveniently expressing the angular coherence parameter as

$$\theta_0 \sim \frac{r_0}{\bar{h}}. \quad (2)$$

We can therefore express the geometric coherence etendue G_c as

$$G_c \sim \frac{r_0^5}{\bar{v}\bar{h}^2}. \quad (3)$$

Slow, low altitude turbulence is clearly advantageous, but it is remarkable that r_0 enters into this expression in such a large power. It is for this reason that adaptive optics and interferometry are driven to sites with the best possible r_0 as the accessible parameter space of astronomical observations is such a steep function of r_0 .

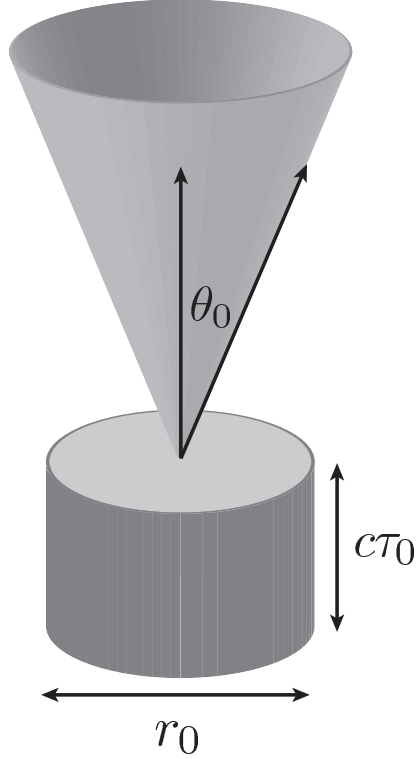


Figure 7. Representation of coherence etendue. By analogy with the concept of etendue (throughput) from optics, a site can be considered to have throughput of coherence $\propto r_0^2 c\tau_0 \theta_0^2$. The coherence etendue characterizes the total fraction of incident light available to coherent detection via phase referenced techniques such as adaptive optics or interferometry.

5.1. Sky Coverage

The most practical expression of the available parameter space for astronomical observations is fractional sky coverage. Such calculations for adaptive optics systems taking into account the multiple sources of error and distribution of stars by galactic latitude are available in the literature.^{24,25} These calculations are relatively complex, folding together not only the technical details of the optics, detectors and control actuators, but also the distribution of stars in the galaxy into a single parameter. It is somewhat remarkable that nearly all modern adaptive optics systems and interferometers have found a fairly narrow range of parameter space operating primarily in the astronomical H and K bands in the near infrared. This is fundamentally because of the steep gain in coherence as a function of wavelength, as r_0 increases with wavelength. A simple calculation of the scaling of sky coverage is illustrative.

The minimum required brightness S_{min} of a guide star scales inversely with the coherence volume,

$$S_{min} \propto r_0^{-3}. \quad (4)$$

For a uniform spherical distribution of sources, the number of sources brighter than some limiting brightness S scales as

$$N_{>S} \propto S^{-3/2}, \quad (5)$$

so the probability of finding guide star P_g scales as

$$P_g \propto N_{>S}(S_{min})\theta_0^2 \sim r_0^{6.5}. \quad (6)$$

Therefore the fractional sky coverage, which is directly proportional to the probability of a guide star, is an extremely steep function of r_0 . This results in a remarkable behavior at which there is a sharp transition between

very small sky coverage, and complete sky coverage at some critical value of r_0 . As r_0 is itself a function of wavelength, the sky coverage therefore depends on wavelength to a large power,

$$P_g \propto \lambda^{7.8}. \tag{7}$$

This is the reason that adaptive optics and interferometry are driven to the longest possible wavelengths as the sky coverage increases so rapidly. However, at mid-latitude sites, beyond $2.5 \mu\text{m}$ observations become difficult due to the rapidly rising sky background and deleterious effects of molecular absorption in the atmosphere, particularly by water vapor.

As the sky coverage is such a steep function of wavelength, there is some critical wavelength at which the sky rapidly transitions from one in which narrow pockets of spatially coherent observations are possible, to one in which the entire sky is available for adaptive optics or interferometric phase referenced observations, as is typical in radio astronomy*. At a good mid-latitude site such as Mauna Kea or Cerro Paranal, the fractional sky coverage is of order 1% at $2.2 \mu\text{m}$, and degrades rapidly at shorter wavelengths. However, it also will rise rapidly at longer wavelengths, becoming 100% at approximately $4 \mu\text{m}$. By unfortunate coincidence, this is a wavelength by which the atmosphere is severely limiting to astronomy, and aside from the $10 \mu\text{m}$ window, there are few regions of transparency at these long wavelengths available until the microwave. Even a relatively small improvement in natural site seeing will, however, open up the regime of fully coherent astronomy to wavelengths that are accessible from the ground shortward of $2.5 \mu\text{m}$.

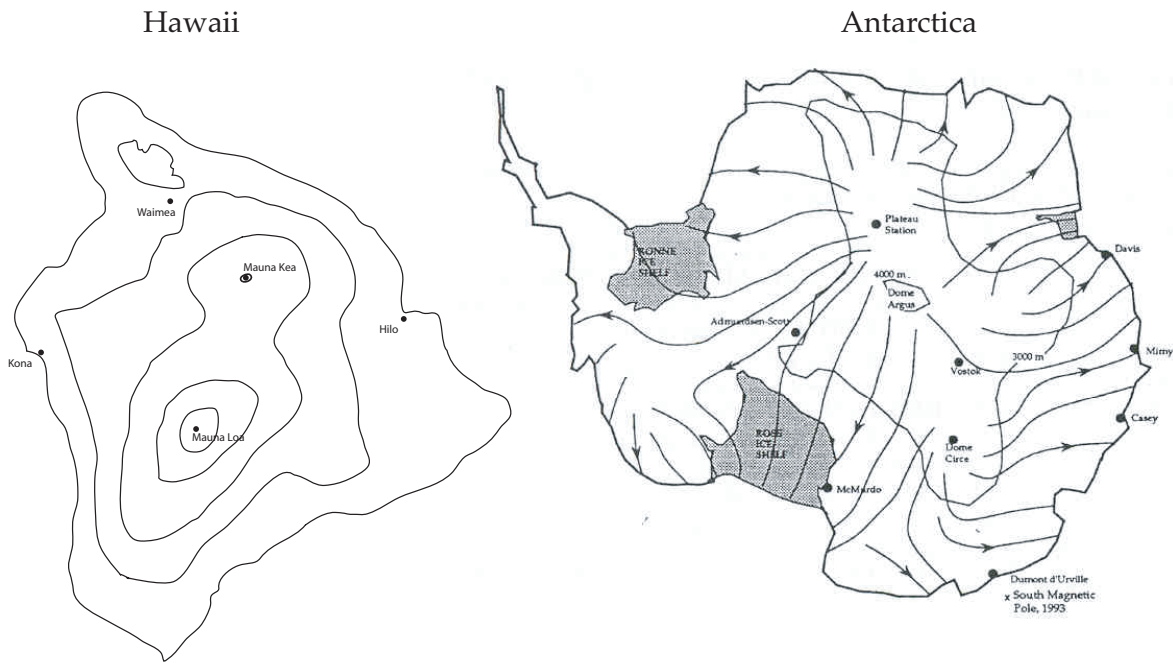


Figure 8. Topographic maps of Hawaii and Antarctica (including katabatic wind contours). High mountain points, and logistical centers are marked in both. It is clear, particularly in view of the katabatic winds, that South Pole is far from the ideal site in Antarctica, and is not necessarily to be compared to the mountain tops in Hawaii.

*There is, of course, an additional consideration related to the noise processes in direct phase or heterodyne detection, but this is not of consequence for this discussion

6. CONCLUSION

Recent seeing measurements at Dome C²⁶ indicate that Dome C has the superb seeing that the arguments in Section 3 suggest should be present in Antarctica. In the median 0.27" seeing as measured by Lawrence et al.,²⁶ the sky coverage as described in Section 5.1 improves by a factor of 100 over 0.5" seeing at Mauna Kea, enabling complete sky coverage in the K band. In the best 10% of the seeing at Dome C, 0.1", the transition wavelength between the coherent and incoherent regimes moves to approximately 1 μ m. Thus, Dome C affords the opportunity for complete sky coverage with adaptive optics and interferometry in the near infrared, opening a large number of astronomical targets to high resolution observations at these important wavelengths for the first time.

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