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Optical Intensity Fluctuations in Re-Entry Object Observations

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Nomenclature

A = projected area of source, m^2
$C_1(0)$ = log-amplitude variance of radiation (dimensionless)
C_2 = second radiation constant, K μm
C_N^2 = atmospheric index-of-refraction structure constant, $cm^{-2/3}$
h = altitude, km
h_t = altitude of tropopause, km
I_1, I_2 = intensity of radiation at wavelengths, λ_1 and λ_2, respectively, W/sr μm
k = wavevector of radiation, cm^{-1}
T = color temperature of source, K
v = integration variable, km
Z = length of viewing path, km
δT = color temperature fluctuation amplitude, K
$\delta \epsilon A$ = emissivity area fluctuation amplitude, m^2
ϵ = emissivity of source (dimensionless)
σ = integration variable, cm^{-1}
$\sigma I_1^2, \sigma I_2^2$ = variances of intensity of radiation at wavelengths, λ_1 and λ_2, respectively, W/sr μm

Introduction

OPTICAL radiation is one source of information on re-entry phenomena. When a re-entering object is observed through the atmosphere, turbulence in the atmosphere between the observer and the re-entering object will induce fluctuations in the observed optical intensity. If data from multiple wavelengths are used to calculate the apparent color temperature of the re-entry object, these intensity fluctuations will result in fluctuations in the calculated color temperature. Conclusions based on optical measurements can be significantly degraded or distorted if these atmosphere-induced effects are not properly interpreted.

The mechanism by which atmospheric turbulence affects the propagation of an optical signal has been well covered in the literature.[1-3] Unfortunately, this theory is usually applied to the case of a ground-based observer looking to space. When the observer is in an aircraft looking at an object that is also in the atmosphere, these effects can be much different. This Note describes the affects of atmospheric turbulence on the observation of a re-entering object when viewed by aircraft-mounted optical instruments. For simplicity, this discussion will be confined to measurements in the visible and near-infrared portion of the spectrum.

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Influence of Atmospheric Turbulence

The normalized variance of the intensity of emissions from a point source, when viewed by an instrument with an infinitesimally small point aperture and an infinitesimally short exposure time,

$$\frac{\sigma I^2}{I^2} = \frac{\langle (I - \langle I \rangle)^2 \rangle}{\langle I \rangle^2} \tag{1}$$

is given by

$$\frac{\sigma I^2}{I^2} = \exp\left[4C_1(0)\right] - 1 \tag{2}$$

where[2]

$$C_1(0) = 65{,}200\, k^2 \int_{\text{Path of propagation}} C_N^2 \int_0^\infty \sigma^{-8/3} \times \left[1 - \cos 10^5 \frac{\sigma^2 v(Z-v)}{kZ}\right] d\sigma\, dv \tag{3}$$

These intensity fluctuations are caused by turbulence-induced atmospheric temperature fluctuations that cause density and hence index-of-refraction fluctuations in the viewing path. When a beam propagates along a path that includes regions of strong turbulence, multiple scattering effects cause the magnitude of turbulence-induced fluctuations to saturate.[3] This saturation occurs when the value of σ_I/I predicted by Eqs. (2) and (3) exceeds roughly 3.16.

Consider the effects these intensity fluctuations have on the calculation of the color temperature of the object radiation from measurements in two spectral bands. For simplicity assume that these bands are in the visible spectrum and are sufficiently narrow that their width may be disregarded. This wavelength region is appropriate for optical measurements of re-entry objects because it lies near the peak of the spectral distribution of the surface emissions of common heatshield materials (such as carbon or silica phenolic) during the peak-heating portion of suborbital re-entry trajectories. Under these conditions, the Wein law is a good approximation to Planck's law. Since the mechanism responsible for these fluctuations should affect the entire optical region of the spectrum, a high degree of correlation should be present in the fluctuations observed at different wavelengths when the fluctuations are below the saturation level. Accounting for these correlations, the normalized amplitude of the calculated color-temperature fluctuations is given by

$$\frac{\delta T}{T} = \frac{-T}{C_2(1/\lambda_1 - 1/\lambda_2)}\left(\frac{\delta I_{\lambda 1}}{I_{\lambda 1}} - \frac{\delta I_{\lambda 2}}{I_{\lambda 2}}\right) \tag{4}$$

Notice that the amplitude of the fluctuations in the calculated color temperature is itself temperature-dependent. The corresponding amplitude of the fluctuations in the calculated normalized emissivity area product of the source is given by

$$\frac{\delta \epsilon A}{\epsilon A} = \frac{1}{(\lambda_1 - \lambda_2)}\left(\lambda_1 \frac{\delta I_{\lambda 1}}{I_{\lambda 1}} - \lambda_2 \frac{\delta I_{\lambda 2}}{I_{\lambda 2}}\right) \tag{5}$$

To illustrate these effects, consider the case of an optical package mounted in an aircraft observing a re-entry object at a slant range of 277.5 km. The altitude profile of C_N^2 is weather-dependent. For the purposes of these calculations, assume that C_N is equal to the constant value 3.55×10^{-10} $cm^{-1/3}$ in the troposphere. Further assume that the stratospheric values are given by

$$C_N = 3.55 \times 10^{-10}(h/h_t)^{-0.873}\ cm^{-1/3} \tag{6}$$

The tropopause-associated spike is superimposed upon the above values. This feature will be modeled by multiplying the above values by a Gaussian centered at the tropopause altitude. This Gaussian will be taken to have a height of 10 and a full width at half maximum of 0.55 km.[4] Consider two tropopause altitudes, 9 km, typical of northern latitudes in the winter, and 15.5 km, typical of equatorial latitudes.

The expected altitude-dependent intensity-fluctuation amplitudes for each tropopause altitude, normalized by the actual intensity values, for two narrow optical bands, one centered at 0.5 μm and the other centered at 0.9 μm, are shown in Fig. 1. These results were obtained by integrating Eq. (3) numerically along an optical path that accounts for both Earth curvature and atmospheric refraction. The corresponding altitude-dependent color temperature fluctuation amplitudes, normalized by the square of the color temperature, are shown in Fig. 2. Finally, the corresponding altitude dependent emissivity area product fluctuation amplitudes, normalized by the actual emissivity area product, are shown in Fig. 3. To illustrate the

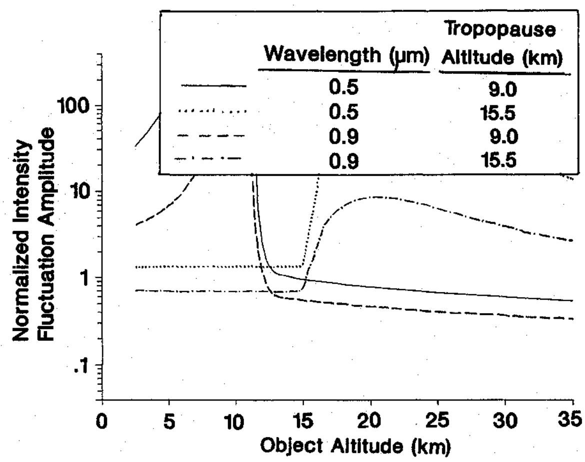

Fig. 1 Normalized intensity-fluctuation amplitudes induced by atmospheric turbulence. These effects saturate at about 3.16. The curves in the figure have been extended into regions where saturation effects dominate to illustrate the overall behavior of Eqs. (1–3).

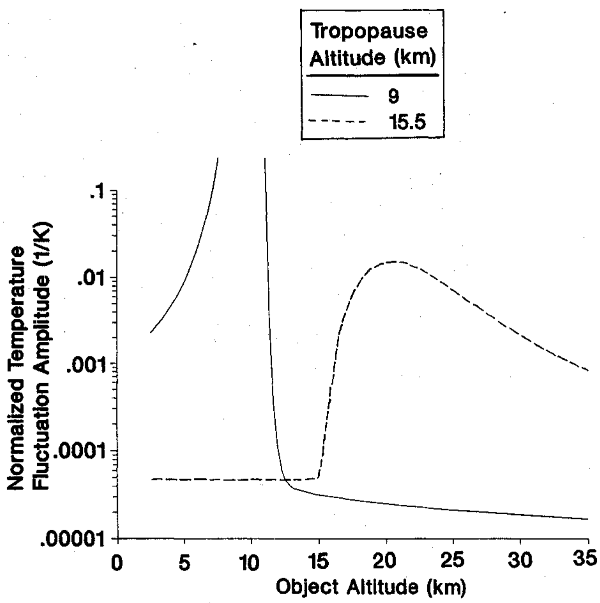

Fig. 2 Color-temperature fluctuation amplitudes normalized by the square of the color temperature. These curves have been extended into regions where saturation effects dominate the intensity fluctuations to illustrate the overall behavior of Eq. (4).

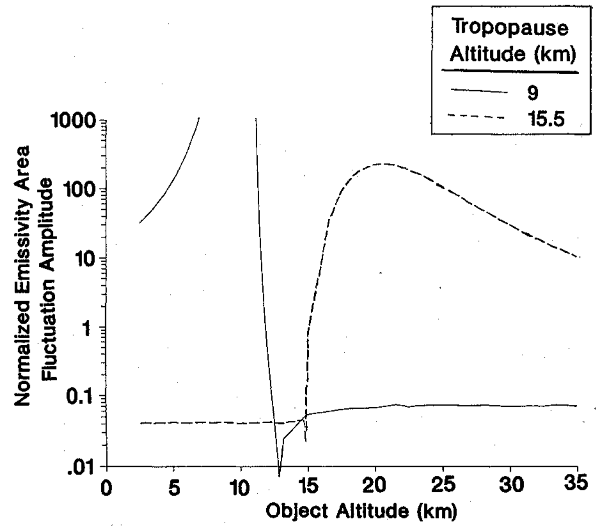

Fig. 3 Normalized emissivity area product fluctuation amplitudes. These curves have been extended into regions where saturation effects dominate the intensity fluctuations to illustrate the overall behavior of Eq. (5).

overall behavior of Eqs. (2–5), the curves in Figs. 1–3 have been extended into regions where saturation effects dominate.

It is immediately apparent that the overall shape of the altitude histories of these fluctuations is strongly dependent upon the altitude of the sensor relative to that of the tropopause. If the sensor is above the tropopause, atmospheric turbulence has little affect on the optical signal until the re-entry object approaches the tropopause altitude. Near the tropopause altitude, very large fluctuations are impressed on the optical signal. When the re-entry object descends below the tropopause, the optical signal again smooths out, although the overall level of the fluctuations is larger when the object is below the tropopause than when the object was at higher altitudes.

When the sensor is below the tropopause, the fluctuations in the optical signal of an object at high altitudes are larger than an object at low altitudes. These fluctuations peak at higher object altitudes than they do in the case where the sensor is above the tropopause. Note that the optical signal from the same object is expected to give a completely different temporal-frequency altitude history when the sensor altitude is changed. Any modulation of the signal due to dynamic motion of the re-entry object will be superimposed upon the turbulence-induced fluctuations.

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