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# ATMOSPHERIC TURBULENCE ON VENUS: EVIDENCE FOR SEVERE MICROWAVE SIGNAL FADING FROM VENERA-4

## ABSTRACT

Mild fading of 1 GHz signals from the USSR probe Venera-4 is reanalyzed to yield a turbulence macroscale $L_o \backsim$ 10-40 m/sec and dielectric permittivity variance $\epsilon^2 > 10^{-7}$ at 25 km above the surface of Venus. These values and the known steady-state conditions imply severe fading of radio communications at GHz frequencies in the lower Venusian atmosphere.

The question of strong effects on radio wave propagation through the atmosphere of Venus due to local turbulence has been raised because it is now known from the Russian Venera-4 probe (which descended on Venus on October 18, 1967) and the American Mariner-5 probe (which occulted Venus on October 19, 1967) that the atmospheric density is far higher than on earth. Turbulence in the earth's atmosphere is unimportant for GHz-frequency wave propagation because its dielectric strength (proportional to air density) is too low.

Recent evidence [1] indicates mild fading of Venera-4 signals at 1 GHz frequency relayed back to earth during descent of the probe of Venus. The fading is ascribed to turbulence in the super-refractive region of the planet's atmosphere, and Kolosov, et al. [1] deduce a value of the dielectric permittivity variance $\epsilon^2 \sim 10^{-9}$ at an altitude of 25 km (12 km inside the super-refractive region), which exceeds typical earth values by more than an order of magnitude. The Russian estimate is based upon an ad hoc assumption of turbulence macroscale $L_o \sim 50$ m, an estimate of the propagation path L that is not weighted for exponentially decreasing air density, and upon gaussian statistics of turbulence (which yield an incorrect integral scale $L_1$). We have reanalyzed the given data and utilized the observed fading rate to <u>deduce</u> a macroscale $L_o \approx 23$ m, and we then obtain $\epsilon \approx 5 \times 10^{-4}$ for typical wind velocities of 5 m/sec. Making the reasonable assumption that $\epsilon$ scales with refractivity and thus with altitude as computed by Stratton [2], we have computed $\epsilon(z)$ as a function of altitude z for a propagation distance of a scale height ($\sim$ 13 km) in Fig. 1. An important fading parameter

$\sigma_\epsilon^2 = k^2\epsilon^2 L_i L$ (k is the wavenumber, $L_i$ the integral scale of turbulence, and L the effective propagation distance) is also given in Fig. 1 for three representative frequencies; since $L_o\epsilon^2$ is independent of the estimate of U only one $\sigma_\epsilon$-curve results for each three $\epsilon$-curves. Propagation theory [3] indicates that the parameter $\sigma_\epsilon$ determines the variance in signal intensity $< (\delta I)^2 >$ around the mean $< I >$ by the relationship $\sigma_I^2 \equiv <(\delta I)^2> / < I >^2 = 1\text{-}\exp(-4\sigma_\epsilon^2)$; consequently severe fading occurs when $\sigma_\epsilon \gtrsim 0.5$, which appears to be the case in the lower atmosphere for signals at 2 GHz and higher frequencies relayed over a distance of about 10 km or more (Fig. 1).

Referring elsewhere [4] to more details we outline the arguments yielding the above results. A corollary of Wheelon's calculation [5] of the average number of zero crossings of phase across the mean yields the following expression for the intensity fading rate f:
$f = 2\pi^{-1}U\sigma_\epsilon M_3/M_1$ where $M_1$ and $M_3$ are the 0 to $\infty$ integrals over dK of $K\Phi(K)$ and $K^3\Phi(K)$ respectively. The central quantity pertaining to turbulence is the three-dimensional spectrum of turbulence $\Phi(K)$ which also figures in the definition of the integral scale $L_i$

$$L_i \equiv \frac{1}{16\pi}\int_0^\infty dK\, K\Phi(K)\left[1-\sin(K^2L/k)/(K^2L/k)\right] \qquad (1)$$

$$\sigma_\epsilon^2 = k^2\epsilon^2 L_i L$$

Note that $L_i$ can be frequency dependent. The Kolmogorov similarity theory of turbulence [Tatarski, Ref. 3] yields the following relationships.

$$\Phi(K) \approx 15.5\, L_o^{-2/3} K^{-11/3} \quad \text{for} \quad L_o^{-1} < K < 5.92\, \ell_m^{-1}$$

$$\ell_m \propto L_o (\mathrm{Re})^{-3/4} \tag{2}$$

$$\mathrm{Re} \propto U L_o \nu^{-1}$$

where $\nu$ is the kinematic viscosity, Re the Reynolds number, and $\ell_m$ the microscale of turbulence. Applying small corrections in $M_1$ and $M_3$ for the regions outside $L_o^{-1} < K < 5.92\, \ell_m^{-1}$ [6], and ignoring the sine-term in Eq. (1), we obtain

$$L_o \approx 2.05 \left(\frac{1}{2}\sigma_I\right)^{8/7} \nu^{-1/7} U^{9/7} f^{-8/7} \tag{3}$$

for mild fading in which case the above definition of $\sigma_I^2$ allows us to replace $\sigma_\epsilon$ by $\sigma_I/2$ in the expression for f. Kolosov, et al. [1] give $f \approx 1\ \mathrm{sec}^{-1}$ and $\sigma_I = 0.36 \pm 0.1$ for their 1 GHz measurements from 12 km inside the super-refractive region. After obtaining (3) we invert the second of Eqs. (1) to obtain $\epsilon$, also replacing $\sigma_\epsilon$ and $\sigma_I/2$. Note that (3) does not depend strongly on the missing constants of proportionality in Eqs. (2); these constants enter multiplicatively into (3) raised to less than their one-fifth power and can consequently be ignored. The estimate depends critically only upon that of velocity U. Ohring, et al. [7] estimate circulation velocities in the atmosphere to be $2\ \mathrm{m/sec} < U < 8\ \mathrm{m/sec}$. We have chosen $U = 5$ m/sec, and the earth's surface value of $\nu$ for $CO_2$ (scaled to the Venus altitude, $\nu \approx 10^{-7} m^2 sec^{-1}$) to obtain the above reported values of $L_o$ and $\epsilon$. Eqs. (1) and (3) provide the scaling law with U; Eq. (2) yields a value of Re $\sim 10^9$

indicating that there is most likely an appreciable inertial subrange of turbulence. In these estimates, Eq. (1) has been amended for exponential decrease of $\epsilon^2$ with altitude; $\epsilon^2 L$ is replaced by $\epsilon^2(z)h/2$ (where $h \approx 13$ km is the scale height, and $z$ the transmitter altitude) for vertical propagation upwards.

From our estimates it is clear that the sine-factor in Eq. (1) plays a role at higher frequencies than 1 GHz because $L/kL_o^2 < 1$. Instead of Eq. (1) we obtain $\sigma_\epsilon^2 = 0.141\epsilon^2 L_o^{-2/3} k^{7/6} L^{11/6}$. Retaining $L = h/2$ we have plotted $\sigma_\epsilon^2$ in Fig. 1 for 2, 5, and 10 GHz, as well as $\epsilon(z) = \epsilon(0)\exp(-z/h)$.

Finally, we believe that Mariner-5 signals may have escaped turbulence fading phenomena because (see Fig. 2) its signals could not penetrate the super-refractive region (where rays coming from higher altitudes are refracted into the surface) and reach the earth. In the occultation experiment $\epsilon^2 L$ is replaced by $\epsilon^2(z)[\pi h(R+z)]^{1/2}$ where $R$ is the planet's radius and $z$ the altitude of the ray's closest approach to the surface. The values of $\epsilon^2(z)$ given in Fig. 1, and the magnitude of $[hR]^{1/2}$ are large enough to allow for some fading of rays passing within 60 km of the surface (believed to have occurred in the Mariner experiment); however, the locations of ray occultation are more than 6000 km from that of the descent of Venera-4 and there might well be discontinuities in $\epsilon(z)$ at the appreciably higher altitudes probed by Mariner-5. Closer scrutiny of Mariner-5 data may in principle reveal weak fading effects, although it is also possible that the accompanying defocussing effects [8] eclipsed these.

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FIGURE CAPTIONS

Fig. 1: Turbulence and fading strength estimates for Venusian atmosphere.

Fig. 2: MARINER-5 and VENERA-4 experiments.

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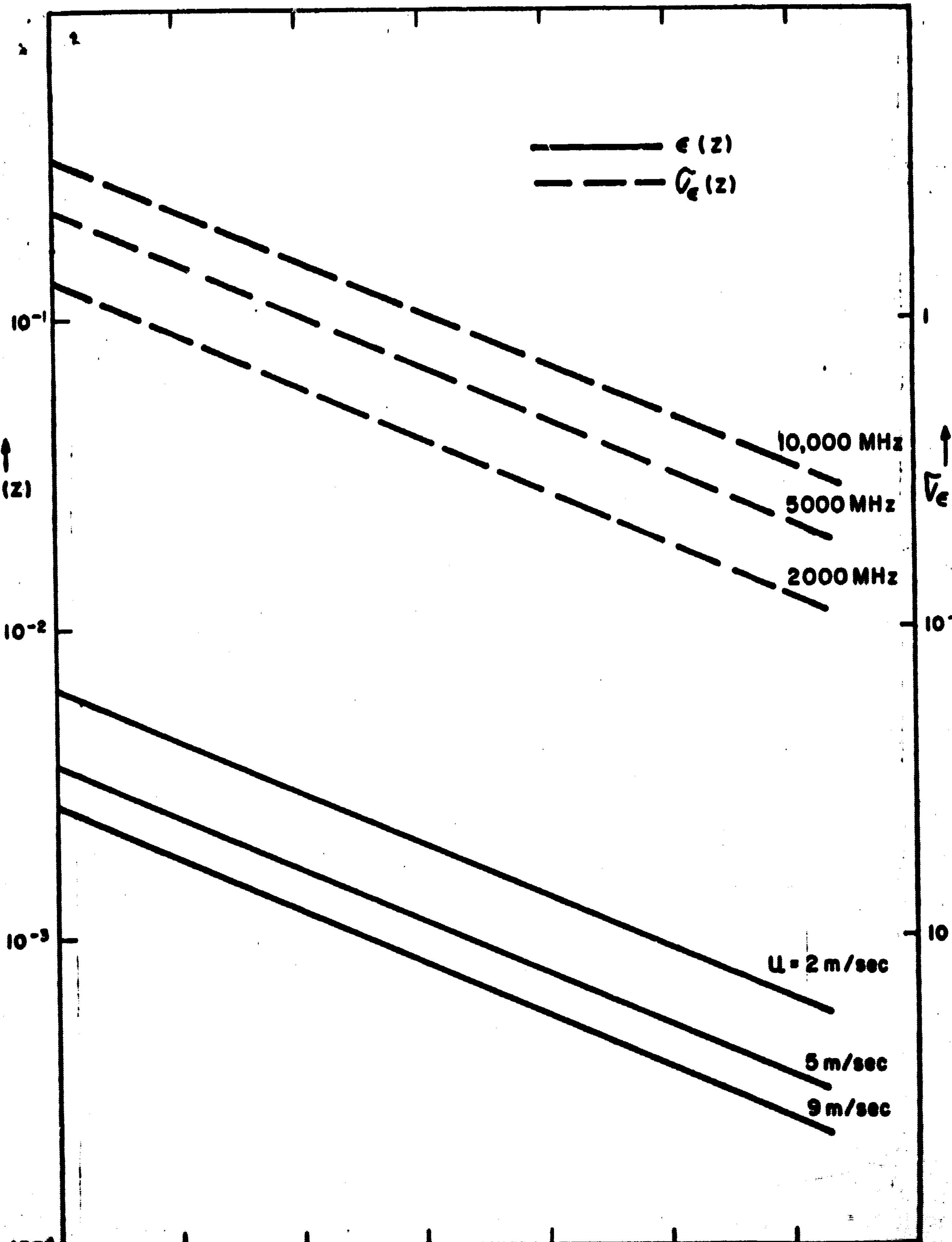
ε (z)
σ_ε (z)
10,000 MHz
5000 MHz
2000 MHz
u = 2 m/sec
5 m/sec
9 m/sec
10⁻¹
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1
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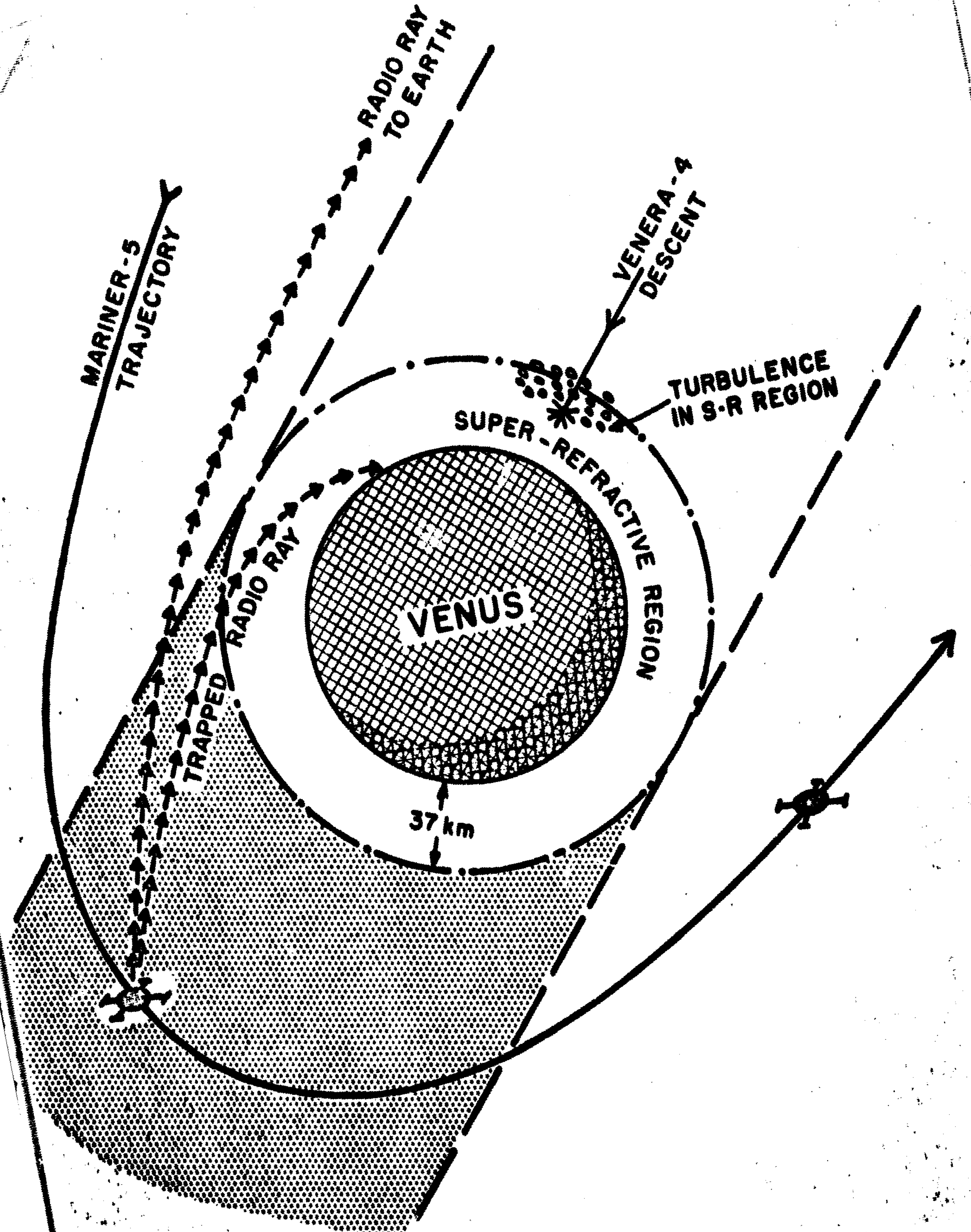
RADIO RAY
TO EARTH
MARINER-5
TRAJECTORY
VENERA-4
DESCENT
TURBULENCE
IN S-R REGION
SUPER-REFRACTIVE REGION
TRAPPED
RADIO RAY
VENUS
37 km