(NASA-CR-158062) A TECHNIQUE FOR REMOTELY MEASURING SURFACE PRESSURE FROM A SATELLITE USING A MULTICOLOR LASER RANGING SYSTEM (Illinois Univ.) 28 p HC A03/MF A01 CSCL 20E G3/36

N79-15292

Unclas 42809

A TECHNIQUE FOR REMOTELY MEASURING SURFACE PRESSURE FROM A SATELLITE USING A MULTICOLOR LASER RANGING SYSTEM

by

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RRL Publication No. 499

Technical Report
January 1979

Supported by

Contract No. NASA NSG-5049

NATIONAL AERONAUTICS & SPACE ADMINSTRATION
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ABSTRACT

The optical path length from a satellite to the earth's surface is strongly dependent on the atmospheric pressure along the propagation path. Surface pressure can be measured by using a multicolor laser ranging system to observe the change with wavelength in the optical path length from the satellite to a ground target. The equations which relate surface pressure to the differential path lengths are derived and the accuracy of the pressure measurement is evaluated in terms of the ranging system parameters. The results indicate that pressure accuracies of a few millibars appear feasible.

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I. INTRODUCTION

Weather forecasting has benefited greatly from the rapid global coverage provided by meteorological satellites. Cloud cover, temperature profiles, pressure profiles and atmospheric wind speed are a few of the important meteorological parameters which can be measured from space. Cloud cover and temperature are readily observed using passive techniques, such as photography and radiometry, while wind speed and pressure measurements require active lidar techniques.[1] Pressure is probably the most difficult of these parameters to measure accurately. Recently, Kalshoven and Korb[2] proposed a DIAL technique for the remote sensing of pressure and temperature. The system observes the pressure and temperature induced changes in the 7600 Å oxygen absorption band. In this paper we describe another approach for measuring atmospheric pressure using a multicolor laser ranging system. The technique is based on the fact that the difference between the optical path lengths from a satellite to a ground target measured at two wavelengths is proportional to the atmospheric pressure at the target.

The Spaceborne Geodynamic Ranging System (SGRS) currently under development at the Goddard Space Flight Center is a single color system which operates at the 0.53 μm doubled YAG laser wavelength.[3] The system, which will use retroflector ground targets, is being designed to provide range resolution approaching one centimeter. Although accurate formulas have been developed to correct the range measurements for the effects of atmospheric refraction, an extensive weather station network is needed to provide the meteorological data required by the correction formulas.[4-6]

To eliminate this problem, a multicolor version of SGRS using the fundamental (1.06 μm), doubled (0.53 μm), and tripled (0.353 μm) YAG laser wavelengths is also being developed.[7] By processing the differential path length measurements using the approach described in the following section, this system could be used to measure surface pressure at the millibar level. In Section II we present the theory and derive the equations which relate surface pressure to the differential path length. In Section III the pressure measurement accuracy is examined.

II. THEORY

The geometry of the satellite and target is illustrated in Figure 1. The optical path length is defined as the integral of the group refractive index along the ray path. Because the horizontal refractivity gradients are small, the one-way optical path length measured by a pulsed laser system is given by

$$R_o = \int_{r_0}^{r_1} dr \, \frac{n_g}{\sin \theta} \quad . \tag{1}$$

n_g is the group index of refraction and θ is given by Snell's law for a spherically stratified medium (see Figure 1)

$$nr \cos \theta = n_0 r_0 \cos \theta_0 \tag{2}$$

where n_0 is the phase refractive index at the target. The atmospheric correction is the difference between the optical range R_0 and the straight-line path length R_s. If n_g is expressed in terms of the group refractivity N_g,

$$n_g = 1 + 10^{-6} N_g \quad , \tag{3}$$

then the atmospheric correction can be written in the form

$$AC = R_0 - R_s = 10^{-6} \int_{r_0}^{r_1} dr \, \frac{N_g}{\sin \theta} + \left(\int_{r_0}^{r_1} \frac{dr}{\sin \theta} - R_s \right) \quad . \tag{4}$$

The first term is the velocity correction while the bracketed term is the difference between the geometric lengths of the ray and straight-line paths.

The atmospheric correction can also be expressed as

$$AC = SC + GC \quad . \tag{5}$$

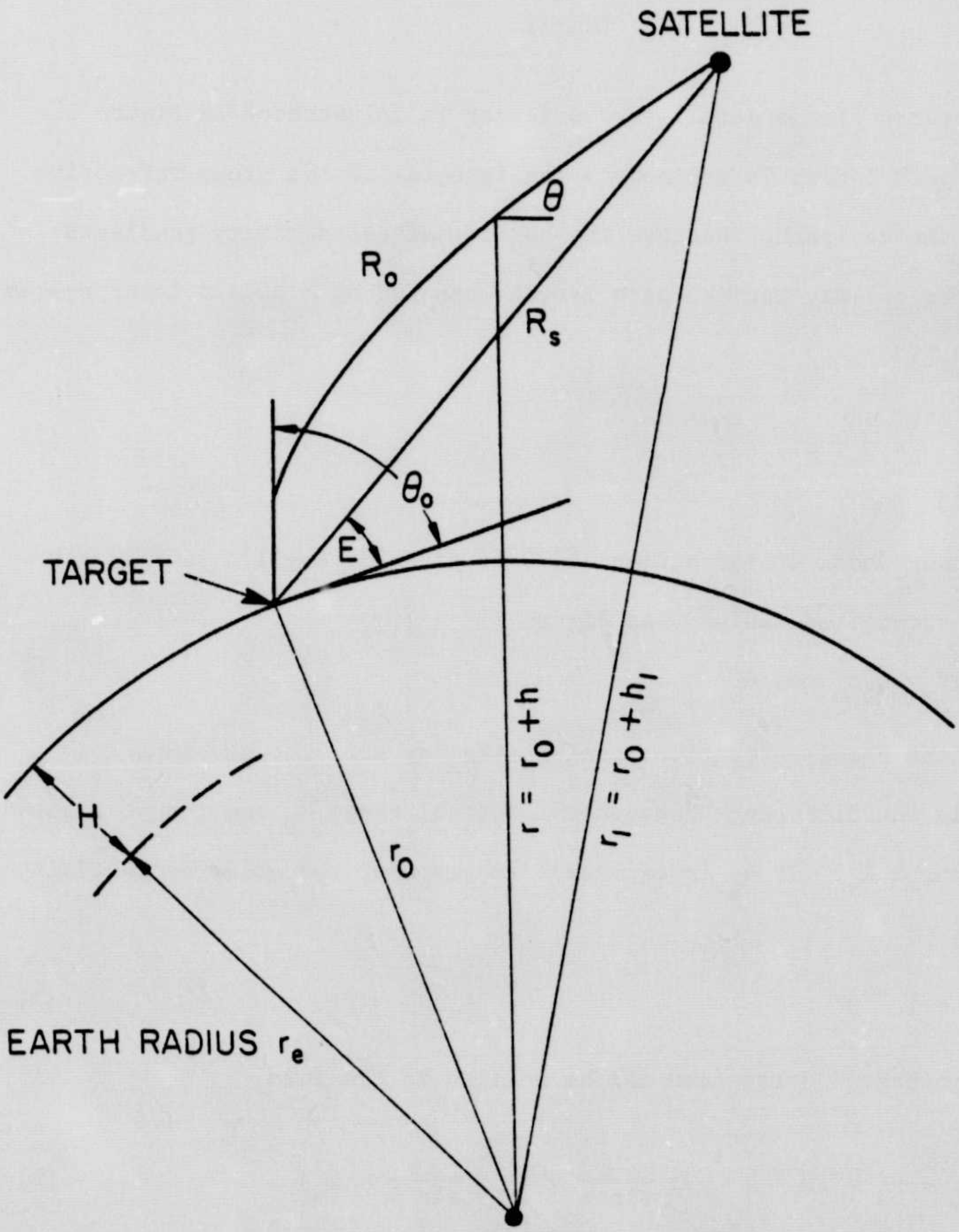

Figure 1. Geometry of the satellite and target.

The spherical correction term SC corresponds to a spherically symmetric atmosphere while the gradient correction term GC includes the effects of horizontal gradients. Marini and Murray[4] have developed an accurate formula for calculating SC in terms of the surface pressure, temperature and water vapor pressure at the target during the satellite pass. The accuracy of their formula has been checked extensively by comparing it with ray tracing data. The results indicate that the error in Marini and Murray's formula is less than 5 mm for elevation angles above 20°.

Recently, we developed an expression for GC in terms of the horizontal pressure and temperature gradients at the target.[5] The accuracy of the gradient correction formula was also evaluated by comparing it with ray tracing data.[6] Because GC contributes less than 1 cm to the total atmospheric correction above 20° elevation, its effect will be neglected and we will restrict our attention to elevation angles above 20°.

The atmospheric correction can be measured remotely from a satellite using either single-color or multicolor laser ranging systems. If the relative positions of the target on the earth's surface and the satellite are known, then the atmospheric correction can be calculated by subtracting the known distance between the satellite and target from the optical path length measured using a single-color ranging system. Because the straight-line distance between the satellite and target must be known to within a few centimeters for this technique to be effective, it is probably not very practical. As an alternative, multicolor systems can be used to determine the atmospheric correction by calculating the difference between the optical path lengths measured at two wavelengths.

Although Marini and Murray's formula can be used to accurately estimate the atmospheric correction at a single wavelength, some of the approximations made in deriving the formula are not valid for estimating the difference between the atmospheric correction at two wavelengths. Fortunately, it is easy to modify Marini and Murray's derivation to eliminate this problem. The approach is to evaluate the integrals in Equation (4) by solving Equation (2) for sin θ, substituting the result into Equation (4) and expanding the integrals in inverse powers of sin E. The resulting integrals are then evaluated by using the perfect gas law, law of partial pressures and the hydrostatic equation to obtain a suitable refractivity profile. The procedure is detailed in references 4 and 8. The most significant terms of the expansion for the round trip atmospheric correction difference are

$$R_{12} = AC_1 - AC_2$$

$$\approx 2\,\frac{f(\lambda_1) - f(\lambda_2)}{F(\theta,H)}\left(\frac{A}{\sin E} - \frac{B}{\sin^3 E} + \frac{C}{\sin^5 E}\right) \qquad (6)$$

where

$$A = 2.357 \times 10^{-3}P + 2.24 \times 10^{-4}e + 1.084 \times 10^{-8}PTK \qquad (7)$$

$$B = 1.084 \times 10^{-8}PTK + 4.73 \times 10^{-8}\,\frac{P^2}{T}\,\frac{2}{3 - 1/K}\,[f(\lambda_1) + f(\lambda_2)] \qquad (8)$$

$$C = 1.5 \times 10^{-13}PT^2\,\frac{K^2}{2 - K} \qquad (9)$$

$$F(\theta,H) = 1 + 0.0026\cos(2\theta) - 0.0003(H) \qquad (10)$$

$$K = 1.163 + 0.00968\cos(2\theta) - 0.00104T + 0.00001435P \qquad (11)$$

$$f(\lambda) = 0.9650 + \frac{0.0164}{\lambda^2} + \frac{0.000228}{\lambda^4} \qquad (12)$$

and

λ = laser wavelength (μm)

e = water vapor pressure at target (mb)

P = surface pressure at target (mb)

T = surface temperature at target (K)

θ = colatitude of target

H = altitude of target above sea level (km)

E = satellite elevation angle.

In deriving Equation (6), we have neglected all terms contributing a few millimeters or less above 20^{o} elevation to the total atmospheric correction.

The atmospheric pressure at the target can be determined by measuring R_{12} using a two-color laser ranging system and then solving Equation (6) for P. Because R_{12} is only weakly dependent on water vapor pressure and temperature, accurate estimates of e and T are not required. This aspect is discussed in detail in the next section. Although the dominant variation of R_{12} with respect to P is linear, the appearance of P^2 in the expression for B (Equation (8)) will introduce quadratic variations which cannot be neglected. Since the variation of K with respect to P is negligible, Equation (6) can be solved for P by using the quadratic formula

$$P = \frac{-b + (b^2 - 4ac)^{1/2}}{2a} \qquad (13)$$

where

$$a = 4.73 \times 10^{-8} \, \frac{f(\lambda_1) + f(\lambda_2)}{T \sin^2 E} \, \frac{2}{3 - 1/K} \qquad (14)$$

$$b = -2.357 \times 10^{-3} + \frac{1.084 \times 10^{-8} TK}{\tan^2 E} - \frac{1.5 \times 10^{-13} T^2}{\sin^4 E} \frac{K^2}{2 - K} \tag{15}$$

$$c = \frac{F(\theta, H) R_{12} \sin E}{2[f(\lambda_1) - f(\lambda_2)]} - 2.24 \times 10^{-4} e \, . \tag{16}$$

III. ERROR ANALYSIS

In a realistic system it will not be possible to determine the parameters R_{12}, E, e and T exactly. Therefore, it is important to assess the effect of errors in these parameters on the accuracy of the recovered pressure. An approximate expression for the root-mean-square (rms) pressure error is

$$\sigma_p = \left[\left(\frac{\partial P}{\partial R_{12}} \sigma_{R_{12}}\right)^2 + \left(\frac{\partial P}{\partial E} \sigma_E\right)^2 + \left(\frac{\partial P}{\partial e} \sigma_e\right)^2 + \left(\frac{\partial P}{\partial T} \sigma_T\right)\right]^{1/2} \quad (17)$$

where $\sigma_{R_{12}}$, σ_E, σ_e and σ_T are the rms errors in R_{12}, E, e and T, respectively. The partial derivatives can be calculated by taking the derivatives of Equation (13) or by applying the chain rule to Equation (6)

$$\frac{\partial P}{\partial R_{12}} = \left(\frac{\partial R_{12}}{\partial P}\right)^{-1} \approx \frac{0.212 \sin E}{f(\lambda_1) - f(\lambda_2)} \text{ (mb/mm)} \quad (18)$$

$$\frac{\partial P}{\partial E} = \frac{\partial R_{12}}{\partial E}\left(\frac{\partial R_{12}}{\partial P}\right)^{-1} \approx \frac{10^{-3} P}{\tan E} \text{ (mb/mrad)} \quad (19)$$

$$\frac{\partial P}{\partial e} = \frac{\partial R_{12}}{\partial e}\left(\frac{\partial R_{12}}{\partial P}\right)^{-1} \approx 0.095 \text{ (mb/mb)} \quad (20)$$

$$\frac{\partial P}{\partial T} = \frac{\partial R_{12}}{\partial T}\left(\frac{\partial R_{12}}{\partial P}\right)^{-1} \approx -\frac{2.55 \times 10^{-6} P}{\tan^2 E} + \frac{3.4 \times 10^{-5} P^2}{T^2 \sin^2 E} + \frac{4.2 \times 10^{-11} PT}{\sin^4 E} \text{ (mb/}^{\circ}\text{C)} \quad (21)$$

The magnitude of $\partial P/\partial T$ is plotted versus elevation angle in Figure 2. Although the pressure sensitivity to temperature error is greatest at the lower elevation angles, its value above 20° is still quite small. At 20° elevation, a temperature error of 50°C would contribute less than one

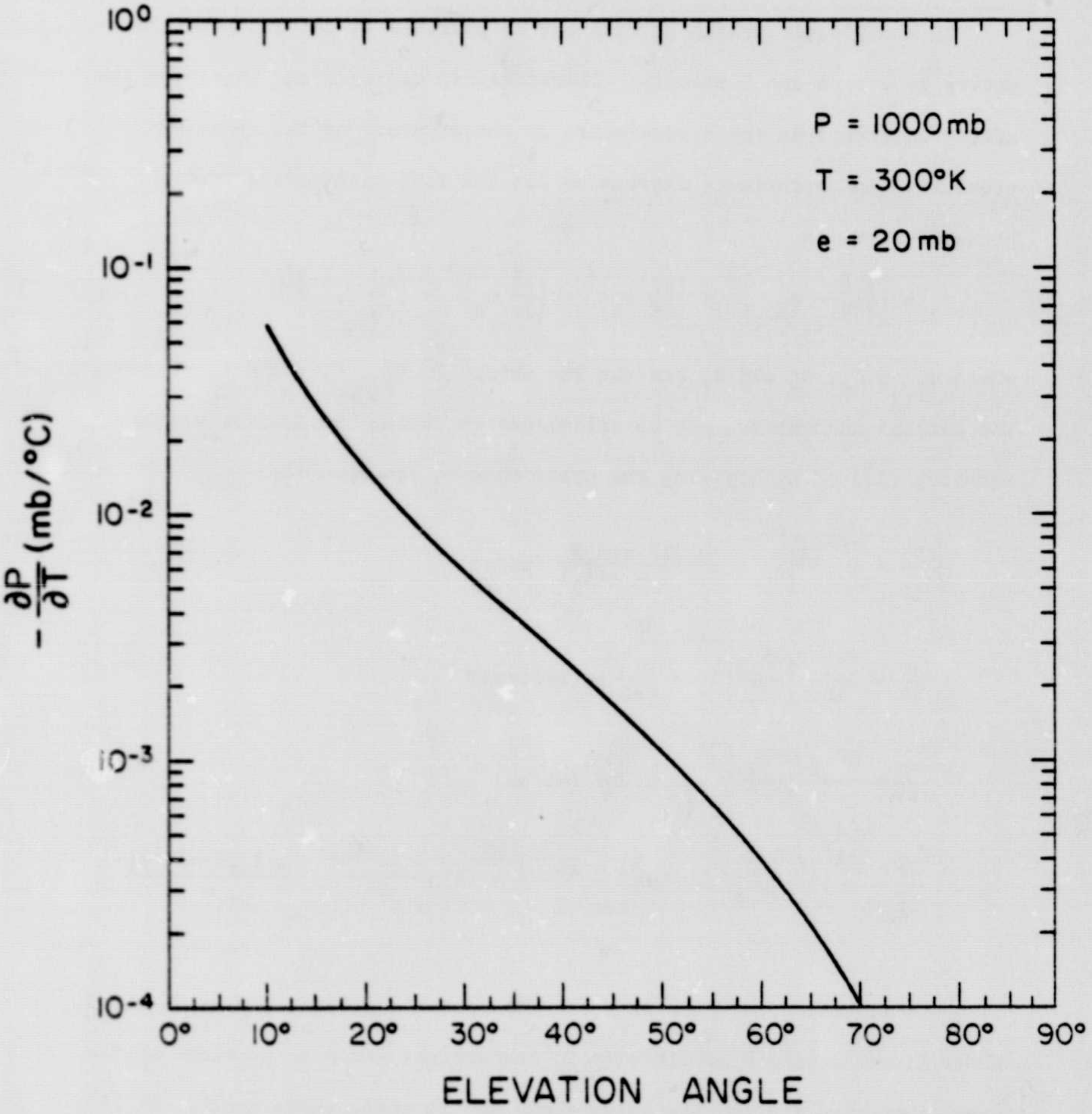

Figure 2. Pressure measurement sensitivity to temperature errors as a function of the satellite elevation angle.

millibar to the pressure error. Thus, only a crude estimate of the surface temperature is required. An accuracy of $20^\circ C$ to $30^\circ C$ is easy to obtain and should be adequate.

The pressure sensitivity to errors in water vapor pressure is constant with respect to elevation angle (Equation (20)). A 10 mb error in water vapor pressure would contribute approximately one millibar to the surface pressure error. Since the water vapor pressure can approach 100 mb when the surface temperature and relative humidity are high, its effect cannot be ignored. It should be possible to predict the water vapor pressure to within 10 to 20 mb using a seasonally adjusted model supplemented with surface data obtained from existing weather stations.

The elevation angle sensitivity (Equation (19)) is plotted versus E in Figure 3. The sensitivity is greatest at the lower elevation angles. At 20° a 1 mrad error in the elevation angle contributes almost 3 mb to the pressure error. The elevation angle can be determined from the laser pointing data. Since pointing accuracies of 100 μrad or less are easily obtained with current technology,[3,9] the resulting pressure errors should be less than a few tenths of a millibar.

The major error source for this technique is the differential path length measurement. The magnitude of the pressure errors caused by errors in the measurement of R_{12} depends on the choice of wavelengths. The sensitivity $\partial P/\partial R_{12}$ is plotted versus elevation angle in Figure 4 for the three possible combinations of the fundamental (1.06 μm), doubled (0.53 μm) and tripled (0.353 μm) YAG laser frequencies. The design of a space qualified multicolor ranging system based on these three wavelengths is currently under study at the Goddard Space Flight Center.[7]

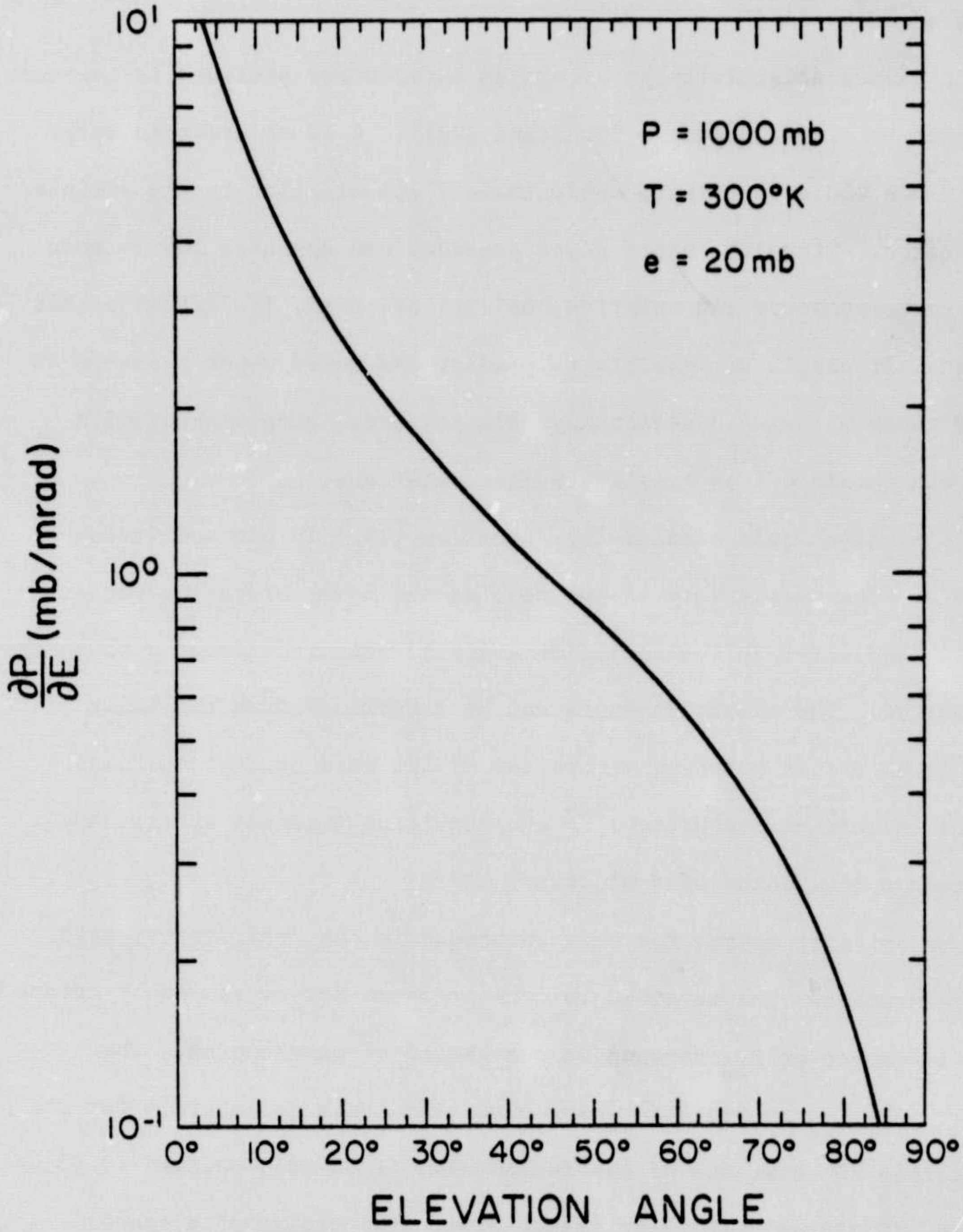

Figure 3. Pressure measurement sensitivity to elevation angle errors as a function of the satellite elevation angle.

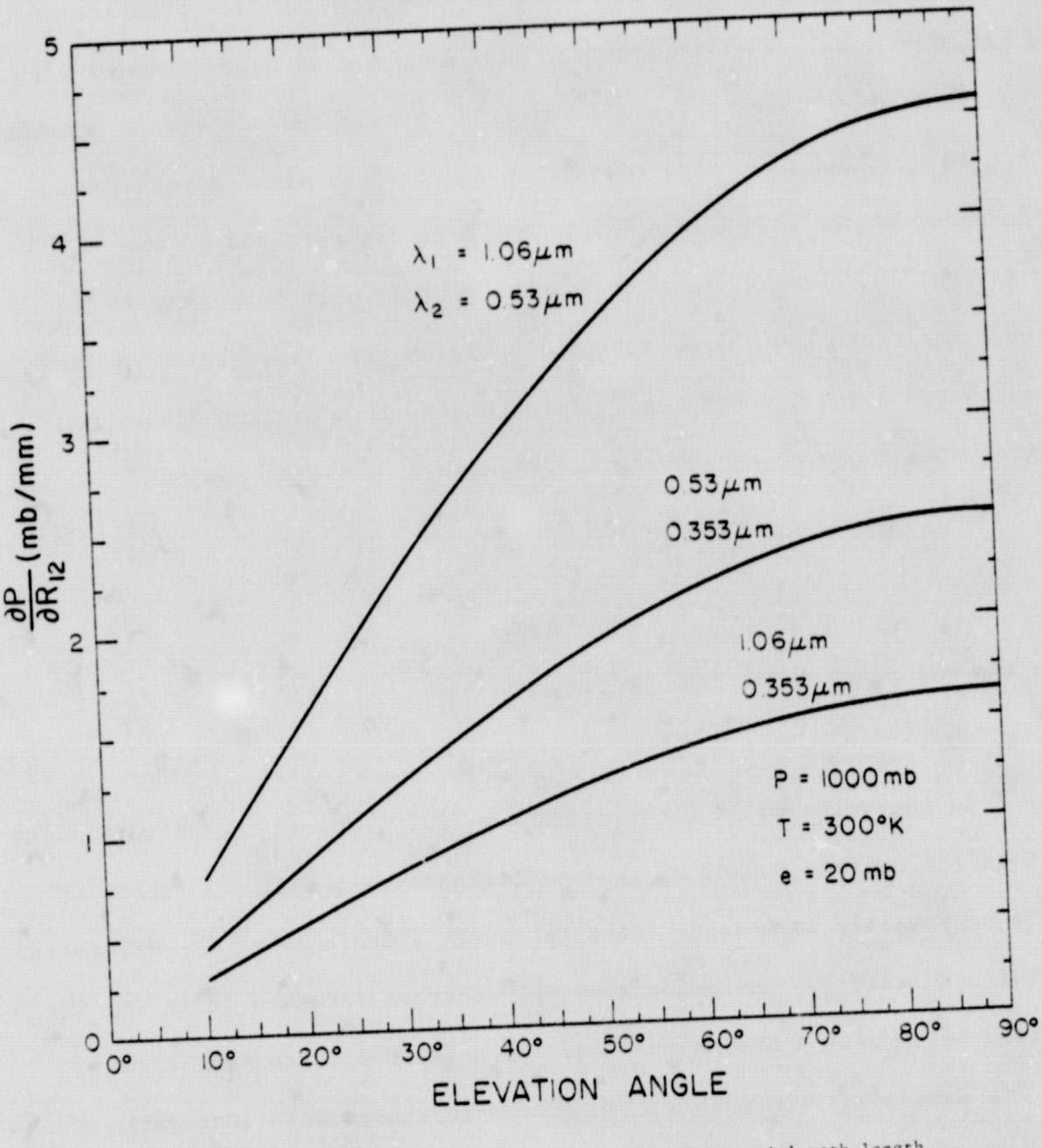

Figure 4. Pressure measurement sensitivity to differential path length errors as a function of the satellite elevation angle.

For the technique to be effective in measuring surface pressure at the millibar level, the differential path length must be determined with an accuracy of at least a few millimeters. Streak tube detectors capable of providing the 5 psec time resolution required to measure path length differences at the millimeter level have been demonstrated in the laboratory.[10] However, the path length error is also dependent on the laser pulse width and shape, target dispersion effects, received signal strength and detection strategy. For example, if a maximum likelihood estimator is employed and the received pulse is a raised cosine

$$P(t) = \begin{cases} \frac{N}{T}[1 + \cos(\frac{2\pi t}{T})] & \frac{-T}{2} < t < \frac{T}{2} \\ 0 & \text{otherwise} \end{cases}, \quad (22)$$

then the rms range error has the form

$$\sigma_R = CT/(2\pi\sqrt{N}) \quad (23)$$

where C is the velocity of light, T is the full width of the optical pulse and N is the average number of photoelectrons per pulse.[11,12] Thus, it should be possible to measure the path length difference at the millimeter level if at least 100 photoelectrons are detected for each pulse and the received pulse widths are on the order of a few centimeters or less.

The sensitivity to path length errors increases with increasing elevation angle while the sensitivity to elevation angle and temperature errors decreases with increasing elevation angle. The optimum elevation angle for minimizing the total pressure error can be calculated by substituting Equations (18) - (21) into Equation (17), and solving for the zero of $\partial\sigma_p/\partial E$. If the small temperature error effects are neglected, the optimum elevation angle is

$$E_{opt} = \sin^{-1}\left\{\left[4.71 \times 10^{-3}(f(\lambda_1) - f(\lambda_2)) \frac{P\sigma_E}{\sigma_{R_{12}}}\right]^{1/2}\right\} \quad . \tag{24}$$

Because σ_E will probably be on the order of 100 μrad or less while $\sigma_{R_{12}}$ will be on the order of millimeters, the optimum elevation angle will normally be below 20°. The total pressure error for the 1.06 μm and 0.353 μm wavelength pair is plotted versus elevation angle in Figure 5 for several values of $\sigma_{R_{12}}$. The elevation angle, water vapor pressure and temperature errors were conservatively chosen to be 100 μrad, 20 mb and 20°C, respectively. Similar curves for the 0.53 μm and 0.353 μm wavelength pairs are plotted in Figure 6. Based upon the results plotted in these figures, pressure accuracies of a few millibars appear feasible if the path length can be measured with an accuracy of a few millimters or less.

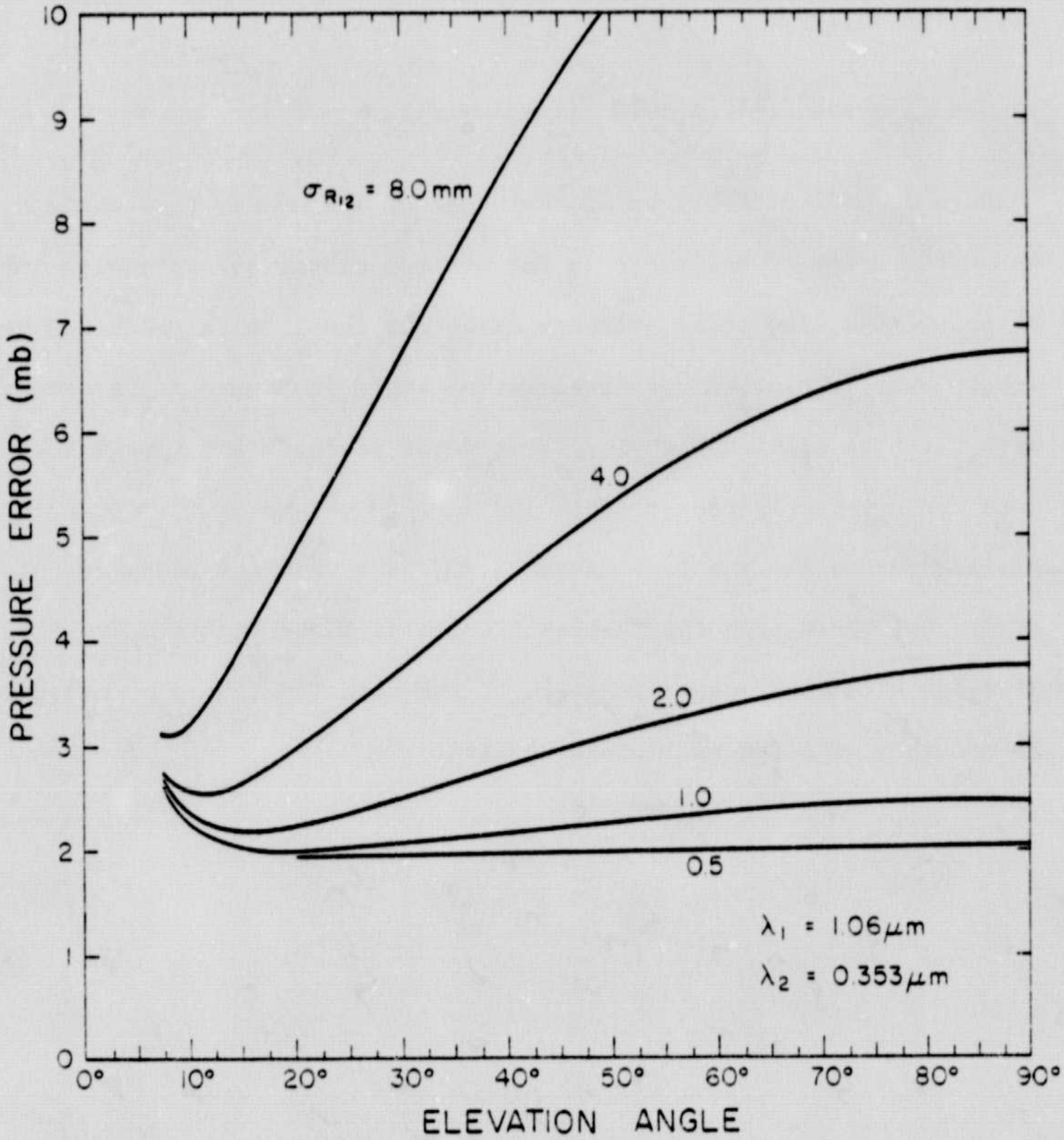

Figure 3. Total pressure error for the 1.06 μm and 0.353 μm wavelength pair as a function of the satellite elevation angle with P = 1000 mb, T = 300°K, e = 20 mb, σ_T = 20°C, σ_e = 20 mb, and σ_E = 100 μrad.

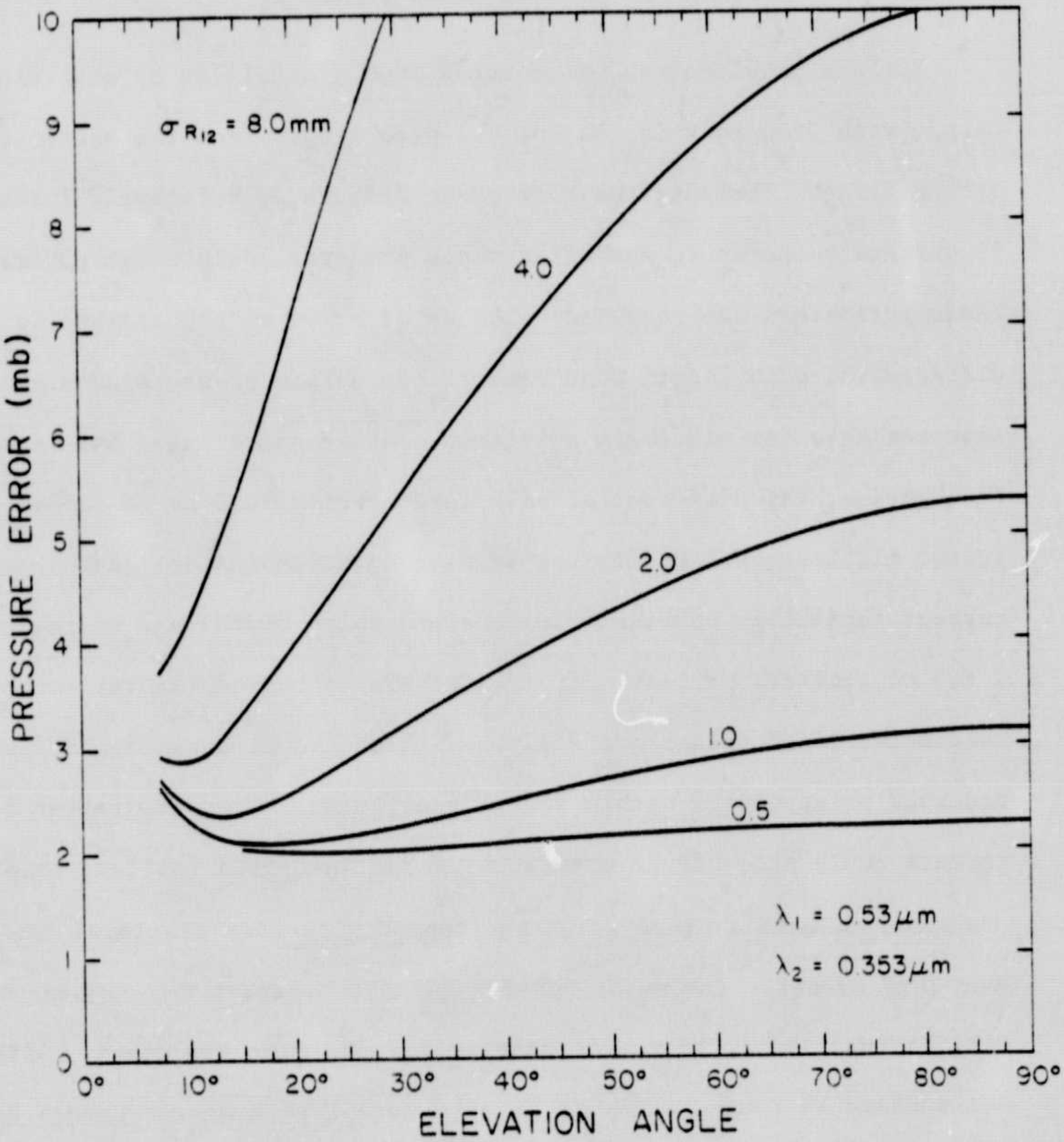

Figure 6. Total pressure error for the 0.53 μm and 0.353 μm wavelength pair as a function of the satellite elevation angle with P = 1000 mb, T = 300°K, e = 20 mb, σ_T = 20°C, σ_e = 20 mb, and σ_E = 100 μrad.

IV. DISCUSSION

Surface pressure can be measured from a satellite by observing the change with frequency in the optical path length from the satellite to a ground target. Because the recovered pressure is relatively insensitive to surface temperature and water vapor pressure, only rough estimates of these parameters are required. The major error source appears to be the differential path length measurement. To obtain pressure accuracies approaching a few millibars using the doubled and tripled YAG laser frequencies, the differential path length error must be no larger than one or two millimeters. Millimeter level accuracies appear feasible with current technology provided the received pulse widths are on the order of a few centimeters or less. If low dispersion retroreflector targets and centimeter laser pulses are employed, it should be possible to keep the received pulse widths within acceptable limits. Adequate retroreflector targets could probably be manufactured and installed for less than one thousand dollars a piece,[7] but the approach is only practical for measurements over land masses. The major benefit of this pressure measurement technique will be realized it it can be adapted for use over the ocean. Although the sea surface is rough, at nadir it acts more like a mirror than a Lambertian reflector.[13] The local surface height of the ocean varies over a range of few meters so that the diffuse components of the scattered pulses will be broadened to a few meters in length. Because of the large wavelength separation, the time-resolved speckle patterns in these diffuse pulses will be uncorrelated. However, there may be specular reflections which do not broaden the pulses and are highly correlated at the two wavelengths. If so, these signal components could be used to determine the path length difference. There has been some work published on the reflection of CW and relatively long pulse (tens of centimeters and longer pulse widths) laser radiation from the ocean surface,[14] but to our knowledge, very little work has been done with centimeter pulses. This problem needs to be investigated further before the utility of measuring surface pressure over the ocean using multicolor laser ranging systems can be adequately assessed.

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