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DEFINITION OF ATMOSPHERIC SCIENCE EXPERIMENTS AND TECHNIQUES-WAKE ZONE MAPPING EXPERIMENTS

FINAL TECHNICAL REPORT

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Shuttle - Aeronomy Experiments for the Tethered Satellite

It has been proposed that a subsatellite system be developed for the shuttle program which would provide to the scientific community a platform for experiments which would be tethered to the shuttle spacecraft orbiting at about 200 km altitude. The subsatellite would be lowered to an altitude of about 105 km and would remain there for several orbits at a time. The concept is that the energy loss from atmospheric drag sustained by a vehicle orbiting at this altitude is large compared to the vehicle energy, but the energy loss sustained by the 100 kg tethered satellite is small compared to the shuttle spacecraft energy. The tether transmits the energy loss to the shuttle.

This report describes the effort under contract NAS8-31772 to describe and recommend experiments which can perform measurements of aeronomic interest onboard or utilizing the tethered satellite concept.

The 105 km Level

The 105 km altitude level on earth is within an altitude band characterized as the transition region. Within this region, the solar EUV is being attenuated rapidly with decreasing altitude, with the majority of energy having been absorbed above this altitude. At or slightly above this altitude the atmosphere starts to diffusively separate since the energy available to maintain mixing rapidly decreases with increasing altitude. The relative importance of eddy and molecular diffusion change roles within this region with molecular diffusion being the major process of transport at the top of the region. Chemical processes involving atomic oxygen vary depending on the diffusion process controlling the transport and the minor constituent composition varies markedly in this region depending on sources of atomic oxygen and the transport sinks.

In general, measurements taken within this region are difficult to interpret. This is due to the fact that this region also represents a transition region in terms of theoretical treatment and/or interpretation of measurements and in the actual instrumentation techniques utilized. Below the transition region, the atmosphere can be considered to be a continuous fluid, with compressible fluid flow theory applicable. Above the transition region, free molecular flow theory is valid and well developed for most measurement interpretations. However, within the region itself the interpretation or direct measurements must be made by an appropriate theoretical mix, usually empirically determined, between the two previous theories.

Also, since the gas density in this region is high enough to present an increased drag problem to orbital vehicles, only reentry type measurements have been performed with satellites in this altitude range to date. Other measurements which have been performed are either from remote sensing type experiments or from sounding rocket experiments which provide data at one latitude, longitude and local time, and do not provide information concerning horizontal variations.

Parameters of Aeronomic Interest

Assuming the tethered satellite attains a 105 km circular orbit, what are parameters of interest to current studies of the atmosphere? Deferring to a later section the question of how to measure and the problems associated with orbital velocities at these low altitudes, a fairly simple answer is possible. We desire information on neutral atmospheric and ionospheric E region composition, temperature and winds versus latitude, longitude and local time, and the variation of these parameters in their time and position coordinates with respect to variations in the solar-geophysical parameters such as the solar flux ($F_{10.7}$) and the geomagnetic activity (K_p). This, of course, is what experimenters have been attempting to do for decades.

A recent publication by Monro, Nisbett and Stick [1976] has shown, with their studies of backscatter data, that the 1972 CIRA does not represent the real atmosphere in the E region and they state the need for more measurements in this region. Donahue and Carignan [1975] also have shown that the temperature gradient of the models in the 90 to 120 km region will not support their green nightglow data. The data of Smith et al. [1974] obtained by direct total pressure measurements through this region support the Donahue and Carignan data, and show considerable variability in this altitude region not accounted for in the models to date.

Much more knowledge of the atmospheric behavior in the 100 to 120 km region is needed before realistic models can be generated. Sounding rocket data and the remote sensing measurements, such as radar backscatter and the airglow monitoring facilities and the chemical releases are useful inputs. However, longitude and latitude variations are needed measurements so that the true dynamical nature of the atmosphere can be determined. The best way to accomplish this is from orbital experiments.

The 105 km Altitude Satellite Environment

Assuming a tethered satellite at 105 km altitude, the 1962 U. S. Standard Atmosphere gives:

λ = mean free path = 38.1 cm

a = speed of sound = 320 m/sec

T_a = ambient temperature = 238 K

The satellite speed will be about 7,500 m/sec with respect to the atmosphere, therefore,

M = Mach number = 23.4

Also,

λ/D = Knudsen number $\simeq$ 1

where D = a characteristic dimension

and $\rho VD/\mu$ = Reynold's number $\simeq$ 1 per cm

where ρ = ambient density = 1.6×10^{-10} gm/cc [1962 USSA)

V = satellite velocity

μ = absolute viscosity

Therefore, the flow is considered to be in the hypersonic transition flow regime. For these conditions we have:

1. Weak, heavily damped shock waves.
2. Elevated satellite surface temperatures due to aerodynamic friction.
3. Excitation and ionization flow fields about the vehicle due to the reflected molecular flux interacting with the ambient gas.
4. Compressed flow causing increased chemical activity in both the neutral and charged species.

Compressible Fluid Flow

Assuming the flow can be treated as a compressible fluid, the Rayleigh equation for the ratio of ram pressure (P_r) to ambient pressure (P_a) is given by:

$$P_r/P_a \simeq 1.29\ M^2 \text{ for high values of } M$$

At 105 km altitude, $T_a \simeq 240$ K [1962 USSA] and for $M = 23.4$

$$P_r/P_a \simeq 726 = \frac{N_r\ k\ T_r}{N_a\ k\ T_a} = \frac{N_r}{N_a} \times 120.5$$

$$\therefore N_r/N_a = 6.03 \text{ outside any gauges}$$

$$N_r(\text{gauge})/N_a = \frac{T_a}{T(\text{gauge})} \times 726 = 225 \text{ for } T(\text{gauge}) \simeq 773°\text{K}$$

Free Molecular Flow

Assuming the flow can be treated as free molecular, the thermal transpiration equation as modified by the stream velocity is given by:

$$n_g/n_a = \sqrt{T_a/T_g}\ f(S) = \sqrt{T_a/T_g}\ 2\sqrt{\pi}S \quad \text{for high S}$$

For:

$$T_a = 240\ \text{K}$$

$$T_g = 773\ \text{K}$$

$$V = 7{,}500\ \text{m/s}$$

$$m = 28\ \text{amu}$$

$$n_g/n_a = 39.2 \text{ for molecular nitrogen}$$

Distribution of First Collisions - the Excitation Field

Medved et al. [1963] have derived an equation for the probable number of first collisions per unit volume about a vehicle traveling at high enough speeds that the reflected particles have sufficient energy to excite or ionize atmospheric particles with which they collide. They give:

$$\rho^i(r) = \frac{\beta q\ H(\cos\theta - \cos\theta_c)}{4\pi r^2\lambda}\,[2(1+\cos\theta)]^{\frac{1}{2}}\exp\{-\frac{r}{\lambda}[2(1+\cos\theta)]^{\frac{1}{2}}\}$$

where

$\rho^i(r)$ = distribution of inelastic first collisions

β = probability of ionization or excitation

q = particle flux = nv_oA

$$H(\cos\theta - \cos\theta_c) = \begin{cases} 1 \text{ for } (\cos\theta - \cos\theta_c) \geq 0 \\ 1 \text{ for } (\cos\theta - \cos\theta_c) < 0 \end{cases}$$

λ = mean free path

θ = angle from velocity vector to the direction of interest

The authors claim this is essentially proportional to the distribution of radiating atoms.

For illustration purposes, assume θ is small enough such that

$$[2(1+\cos\theta)]^{\frac{1}{2}} \simeq 2 \quad (\text{for } \theta_c = 45°,\ [2(1+\cos\theta_c)]^{\frac{1}{2}} = 1.85)$$

and

$$q = Nv_o\ 2\pi r_o^2 \cos\theta \quad (\text{hemispherical reflecting source of radius } r_o)$$

then

$$\rho^1(r) = \frac{\beta N v_o\ 2\pi r_o^2\ \cos\theta}{4\pi r^2\ \lambda} \times 2 \times \exp\{-2\ r/\lambda\}$$

or

$$\frac{\rho^1(r)}{\beta N v_o} \approx \frac{r_o^2 \cos\theta\ \exp(-2\ r/\lambda)}{\lambda^3\ (r/\lambda)^2}$$

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Integrating over the volume, we get the column intensity of radiation at the spacecraft per unit excitation flux and area:

$$I_c = \int \frac{\rho^1(r)}{\beta N v_c} \frac{dV}{(4\pi r^2)} = \frac{r_o^2}{\lambda^2} \int_{r_o/\lambda}^{\infty} \int_{0}^{\theta_c} \int_{0}^{2\pi} \frac{\exp(-2r/\lambda)\cos\theta\sin\theta d(r/\lambda)d\theta d\phi}{r^2/\lambda^2\ 4\pi}$$

$$= \frac{1}{2} \frac{r_o^2}{\lambda^2} (1-\cos^2\theta_c) \int_{r_o/\lambda}^{\infty} \frac{\exp(-2\ r/\lambda)}{(r/\lambda)^2} d(r/\lambda)$$

$$I_c = \frac{1}{2} (r_o/\lambda)^2 \sin^2\theta_c \left\{ \frac{\exp(-2\ r_o/\lambda)}{r_o/\lambda} + 2[-E_1(-2\ r_o/\lambda)] \right\}$$

Where $-E_1(-2\ r_o/\lambda)$ is the exponential integral as tabulated in Jahnke, Emde and Lösch [1960].

Now, the absolute intensity at the spacecraft is not known until the β is determined. However, we know that at 150 km altitude the Visual Airglow Experiment (VAE) on board the AE satellite observed an intense glow about the spacecraft which precluded useful measurements of the natural airglow. Therefore, the variation of the I_c with respect to r_o/λ, or λ/r_o and altitude would be useful on a comparative basis. This is shown in Figure 1 and 2. Figure 2 shows that the intensity of radiation at 115 km should be at least one order of magnitude greater than the intensity at 150 km which suggests that the induced airglow by the spacecraft will be significant.

Steady State Distribution of Ionization

Medved et al. [1963] also derived an equation which gives the distribution of ionization about a spacecraft. They give:

$$N_i(r',z) = \frac{\beta q}{\pi \lambda v_o z} e^{-2z/\lambda} \quad \text{for } r'/z < \theta_c$$

where

β = probability of ionization

q = flux of particles reflected from spacecraft

λ = mean free path

z = distance from spacecraft along velocity vector

r'= radius from z to point of interest

$$\therefore \frac{N_i(r',z)}{\beta N_a} = \frac{v_o \pi r_o^2}{\pi \lambda v_o z} e^{-2z/\lambda} = \frac{r_o^2}{\lambda z} e^{-2z/\lambda}$$

where r_o = radius of the spacecraft.

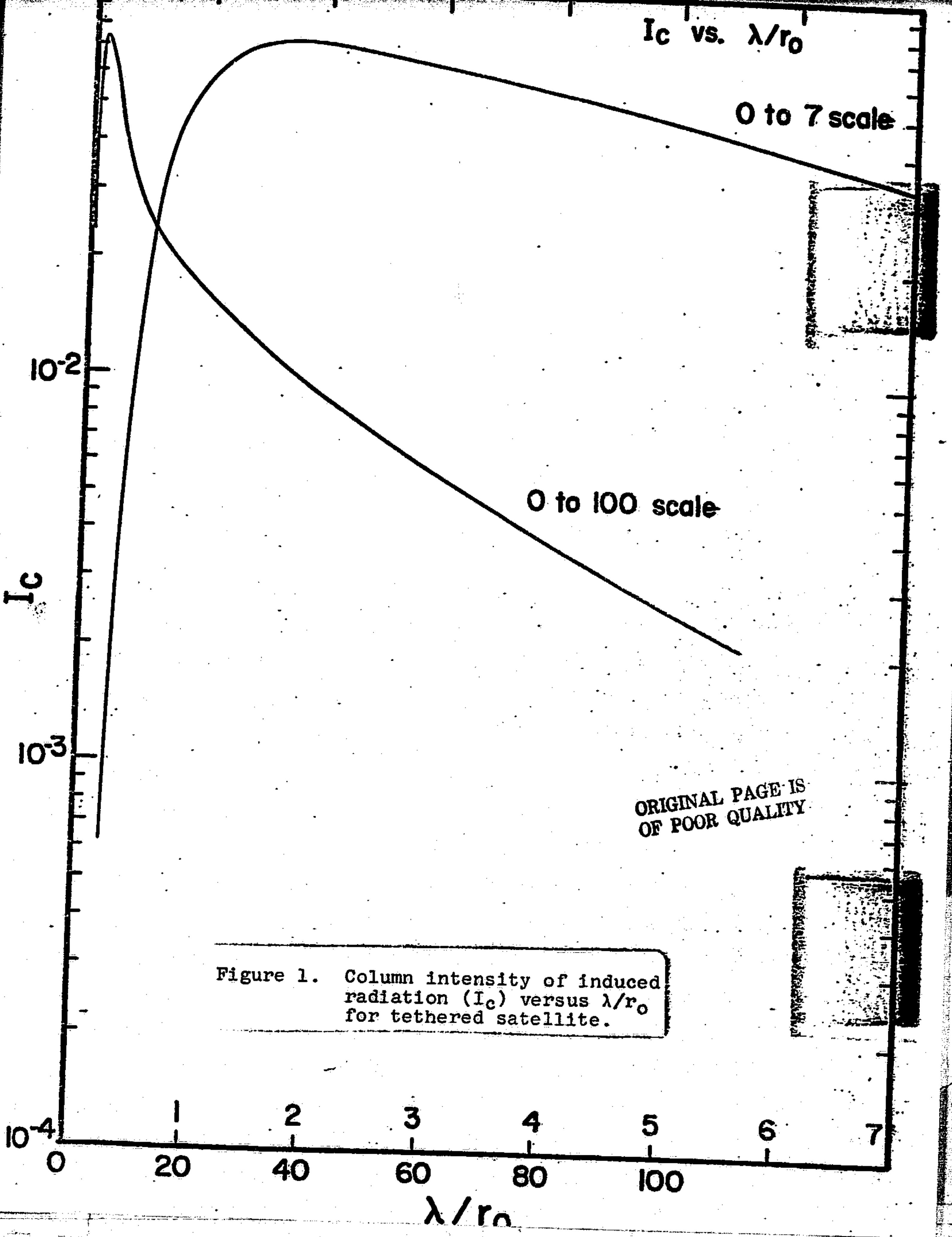

Figure 1. Column intensity of induced radiation (I_c) versus λ/r_o for tethered satellite.

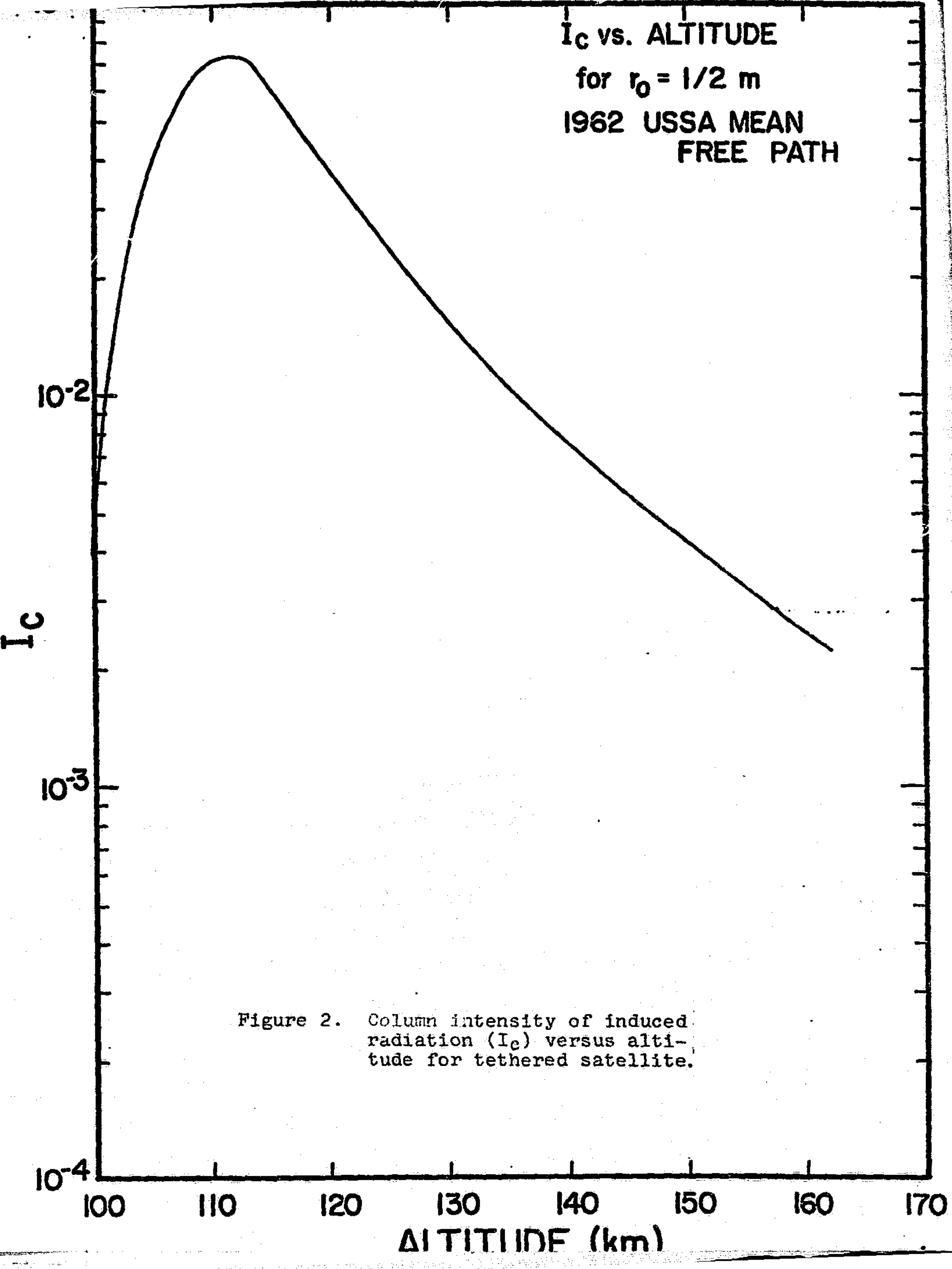

Figure 2. Column intensity of induced radiation (I_c) versus altitude for tethered satellite.

Assuming an r_o of 0.5 m, the ionization ratio at r_o in front of the spacecraft ($z = r_o$) is then given by:

$$\frac{N_i(0,\ r_o)}{\beta N_a} \approx r_o/\lambda\ e^{-2r_o/\lambda}$$

These results are plotted in Figures 3 and 4. This is used as an example calculation for the purpose of showing how the distribution of ionization varies with r_o/λ and with altitude at a point near the spacecraft.

Measurement Techniques to Investigate

The previous sections of this report were estimating the environment of the satellite to establish what limitations are placed on measurements of the atmospheric parameters in the 105 km altitude region. This section of the report will discuss possible measurement techniques which may be used.

One environmental problem not discussed is that of the tethered satellite temperature. It is predicted that aerodynamic heating will raise the skin temperature to approximately 500 C at 105 km altitude. This of course would eventually be the approximate internal temperature of instrument packages, without the use of cooling. This in itself is a major engineering problem for the electronics. This particular problem is not discussed in this report except as it pertains to one particular technique which utilizes cryogenic cooling.

The techniques discussed in this section will be divided into two catagories. The first are active experiments which are on board the tethered satellite and make measurements directly utilizing on board power and signal handling. The second category includes experiments which are called passive. These experiments use the spacecraft as the signal generator, radiation generator or reflector for experiments which are primarily operated remotely from the shuttle or ground.

Active Experiments

Total Pressure Measurement. A very useful experiment would be the measurement of the total (ram) pressure in a 105 km circular orbit. The diurnal and/or latitudinal variation of pressure at this altitude has not yet been established. The ram pressure level is approximately 10^{-4} torr, allowing a reasonably simple device, such as a capacitance monometer, to be used for the measurement. Although the transition flow theory is not well developed at the Mach numbers to be encountered, the relative variation of pressure would be useful information. A possible separate measurement at some point along the orbit, such as a sounding rocket flight near the satellite orbit, could establish a calibration point for quantitative interpretation of the satellite measurements.

Mass Analysis. Ion and neutral composition measurements in the usual sense are most likely useless at 105 km due to the induced environment. However, useful measurements could be made while lowering and raising the satellite, probably at altitudes above 120 km.

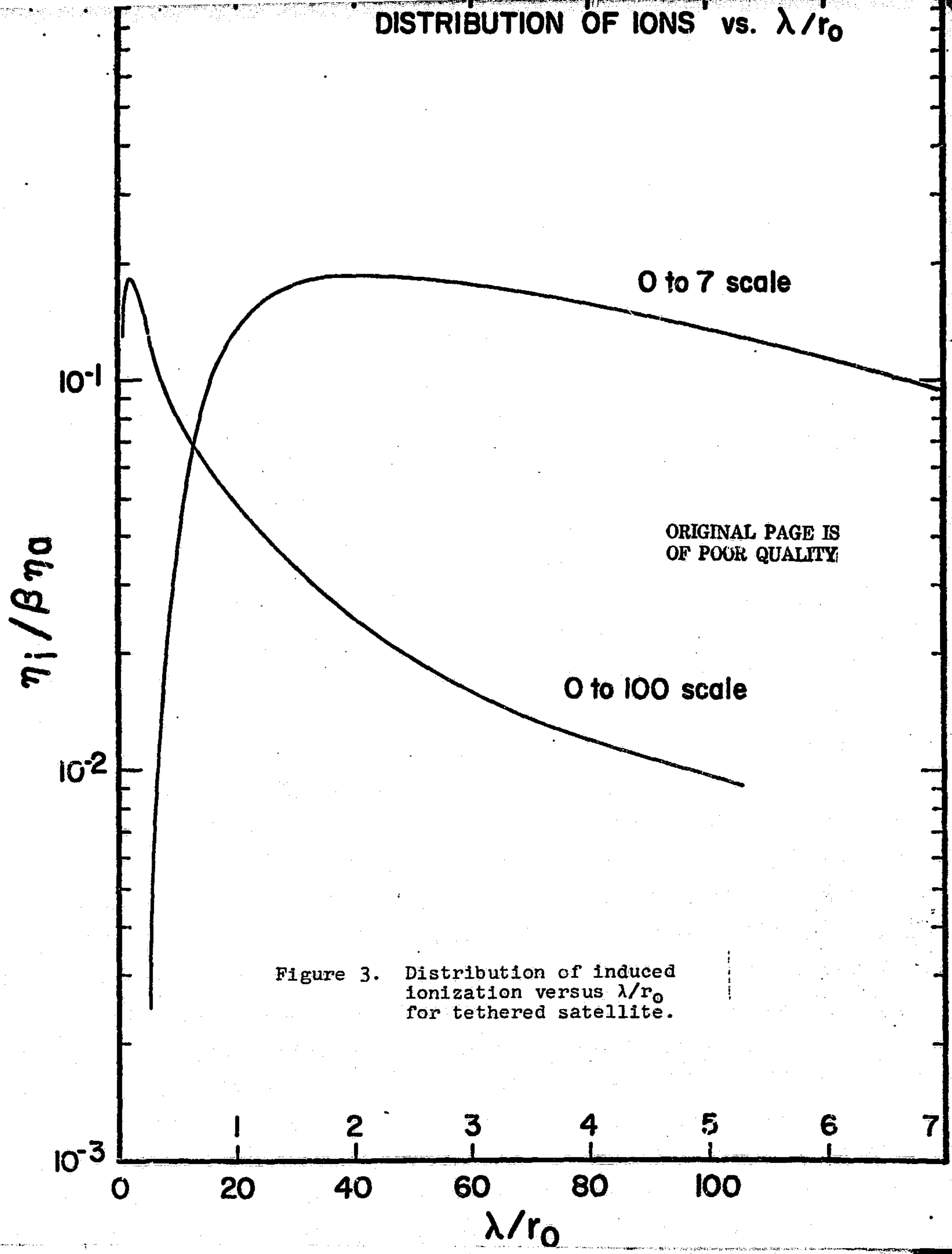

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Figure 3. Distribution of induced ionization versus λ/r_0 for tethered satellite.

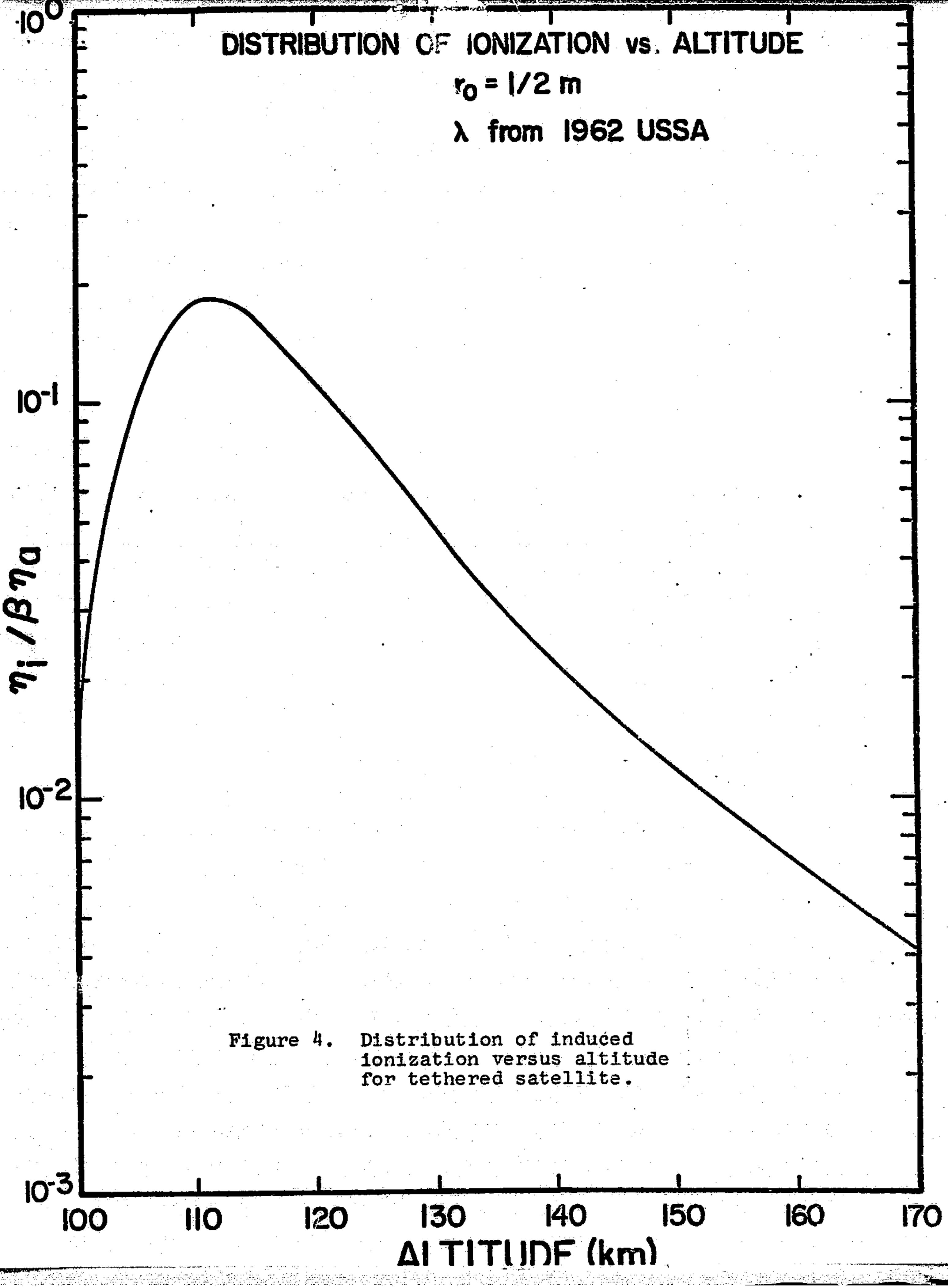

Figure 4. Distribution of induced ionization versus altitude for tethered satellite.

One possibility for making meaningful measurements at 105 km would be to utilize a cryogenically cooled system similar to that developed by Dr. U. von Zahn's group at the Physikalisches Institut in Bonn. Offermann and Scholz [1973] report on a system which freezes out the shock wave and eliminates the interaction of the reflected particles with the incoming ambient particles. Another advantage of the cooled source is to eliminate the molecules which have collisions with the internal walls of the mass spectrometer which could chemically change and alter the interpretation of the ambient composition. The heat load at which this source was tested was 1.9 W/cm^2, or roughly equivalent to that which they would experience at 80 km altitude. The heat load at 107 km on the tethered satellite is of this same order. The length of time one could operate the mass spectrometer system would depend on the amount of cryogenic material carried on board, and on the actual heat load. A very short term measurement may well be worth the effort, and the system would be recyclable.

Chemical Release Systems. Chemical releases in the form of chemiluminescent or smoke trail tracer material could be performed on board the tethered satellite. The released plumes could be observed from the ground or from the shuttle to provide information on atmospheric winds, turbulence, and diffusion porperties at the 105 km level.

Resonance Fluorescence Experiment

An experiment to globally map the vertical concentration profiles of NO, O, N, H, H_2, H_2O and N_a can be performed using atomic and molecular resonance fluorescence. The experiment would consist of: (1) a cluster of plasma discharge lamps, each emitting resonance radiation radially from the subsatellite and (2) a group of scanning ultraviolet spectrometers which would detect the backscattered resonance radiation at differing positions along the beam. It would, thus, be possible to both determine the absolute concentration of the fluorescing species as well as determine whether surface effects near the vehicle are critical.

Passive Experiments

Experiments in this category are those which require no active manipulation of instrumentation on board the tethered satellite. Such things as reflectors of radio or light sources on board the shuttle (LIDAR) for absorbtion measurements, and possible light or radio sources on board the tethered satellite which are monitored remotely, are the types of experiments which are defined here as passive. Also, the tethered satellite itself is an infrared source, which could be intensified by lowering it still further to increase the aerodynamic heating. Specifics of these types of experiments will be left to those with expertise in this field.

Sample Tethered Satellite Mission

Assuming the tethered satellite is to be deployed as predicted in 1975, it will take some 10 hours to lower it to 107 km altitude. The maximum rate of descent will be approximately 27 km per orbit. During deployment, the satellite will be in an environment for which many measurement techniques have been devised. However, there have been few measurements in near circular orbit below 200 km altitude, due to the shortened lifetime of satellites at these lower altitudes. Therefore, measurements performed from the tehtered satellite during deployment would add considerably to our knowledge of the upper atmosphere and would be relatively straight forward.

A list of aeronomy experiment which could provide useful measurements from the tethered satellite during deployment would be too extensive to provide here since all successful experiments performed to date would be included. However, a sample mission will be described which is felt to be feasible and would provide very useful data.

The complement of instruments for one such mission could be a neutral mass analyzer, a total pressure gauge, a gas or smoke trail release, an ion mass anayzer, and a resonance fluorescence experiment. This grouping of instruments would be able to map out the atmospheric parameters including minor constitutents from 200 km down to about 105 km altitude.

Assuming the tethered satellite and mass analyzer are will outgassed, neutral and ion composition would be measurable as soon as the instrument could be turned on following initiation of deployment. These measurements could continue down to about 130 km altitude, where the density would be high enough to endanger the ion source of the mass analyser. The mass analyser would be turned off at this altitude. The resonance fluorescence experiment and the total pressure gauge would have been operating and making meaningful measurements at some altitude above this and would now become the primary neutral density experiments, including minor constituents, down to the lowest altitude of the tethered satellite. The ion mass analyser would be operational throughout the mission although interpretation of the results at the lower altitudes may be difficult. In circular orbit at 107 km, the total pressure instrument will be monitoring the variability of total pressure versus latitude, local time, etc. depending on the orbital inclination. The gas release system would be operated periodically in coordination with monitors on the ground or on the shuttle spacecraft, measuring atmospheric winds and turbulence.

At the completion of the mission, if power is available, the instrument could operate during retrieval as they did during deployment. In any case, all instruments would be recyclable and available for future missions.

Conclusions

The tethered satellite concept would be a useful tool to aeronomists. The altitude region of operation has been previously unobtainable for satellite measurements. Once the system becomes operational, the costs per mission would be minimal and as instrumentation development progresses, more and more significant information concerning the 105 km level and the variability therein will be available to aeronomists.

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