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Technical Memorandum - 28

# FEASIBILITY OF MULTI-SATELLITE OCCULTATION (REFRACTION) MEASUREMENTS FOR METEOROLOGY

For

Advanced Instrumentation and
Sensor Engineering Program Office (SAL)
National Aeronautics & Space Administration
Washington, D. C.

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# FEASIBILITY OF MULTI-SATELLITE OCCULTATION (REFRACTION) MEASUREMENTS FOR METEOROLOGY

by

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# FEASIBILITY OF MULTI-SATELLITE OCCULTATION (REFRACTION) MEASUREMENTS FOR METEOROLOGY

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## SUMMARY

This study considers the feasibility of the multi-satellite occultation (refraction) technique for obtaining global profiles of atmospheric density and pressure. Two concepts are discussed in detail; one was developed by Professor B. Lusignan of Stanford University (ref. 1) and the other by Professor J.V. Harrington of MIT and Dr. M.D. Grossi of the Raytheon Company (ref.2). The stellar occultation technique and a microwave cross-beam correlation concept also were investigated briefly.

The concept advanced by Professor Lusignan has a satellite configuration consisting of a mother satellite and six daughter satellites, all in the same polar circular orbit. The satellites are spaced so that radio waves from the mother to each daughter pass through the atmosphere, with the path to each succeeding daughter coming closer to the surface of the earth. The path length, as measured by phase and Doppler frequency measurements on each mother-daughter pair, is an indication of the refractivity of the atmosphere along the radio path. Any difference between the straight line separation and the measured radio path length separation, is caused by bending of the radio signal and retardation of the velocity of transmission of the signal. The refractivity of the atmosphere is proportional to its density and

the density along the path is greatest at the point closest to the earth's surface. Thus the measurement can be considered to be representative of conditions at or near the point of minimum altitude.

This configuration gives measurements at five altitudes on a continuous, periodic, global basis, as the satellites orbit the earth. The link between the mother and closest daughter is used for detection of orbital perturbations and other effects that may produce relative motion between the satellites.

The Raytheon Company technique utilizes only two satellites. However, these are in different orbits, and the satellites continuously approach and move away from each other. When the radio path between the satellites passes through the atmosphere, atmospheric refraction measurements may be made in a fashion similar to the Mariner Mars experiment, measuring only the Doppler shift. The reason that absolute path length need not be known is that measurements will begin above the atmosphere, while all measurements using the Stanford technique will be influenced by the atmosphere. The Raytheon configuration provides continuous vertical coverage from the top of the atmosphere to the earth's surface, as opposed to having measurements at a distinct number of levels. During the time when the path is above the atmosphere, ionospheric electron density measurements can be made using the same technique of measuring refraction if a frequency sensitive to ionospheric influences is used. The areal coverage is irregular, depending on the location of the occultations. Several such satellite pairs would be required in an operational system to provide the required density of sample points.

The occultation-refraction techniques face many problems before they can be successfully implemented. To obtain the required accuracy in density and pressure, orbital path accuracies of fifty meters or better are needed. This is slightly pushing the state-of-the-art. The multi-satellite technique of Stanford University, in addition, requires a large amount of station-keeping ability onboard each satellite since the relative satellite positions are highly critical. At low altitudes, below about 10 Km, water vapor in the atmosphere contributes significantly to the refractivity. Water vapor must be measured to 1% to provide accurate density measurements at the 800 mb level. Schemes for measuring the water vapor have been proposed, but they are still under development and it is unknown whether any will be successful. Multi-path, ducting, and scintillation effects may also prove to be severe problems in the operation of this type of system.

The data inversion technique also requires further study. There is a unique radio path length for each satellite separation and intervening atmosphere combination, but there are many atmospheres that could produce a measured path length. Professor Lusignan and Dr. Grossi have each adopted an iterative approach to the problem of deducing the density from phase path measurements. In both cases, a model atmosphere is assumed and the corresponding radio path calculated. The assumptions are based on independent measurements, previous occultation measurements, and general knowledge of the area being measured. The model atmosphere is changed until the calculated path length agrees with the measured path length. Thus, a global vertical density profile is derived.

An occultation system employing one satellite whose instruments lock onto a star and track the star as it is occulted by the earth was one of the first proposals to provide global density profiles. In 1962, F.F. Fischbach of the University of Michigan proposed a very narrow-beam telescope on board a satellite for this purpose. The multi-satellite techniques now hold greater promise than this star tracking scheme because of its many inherent limitations. The star tracker can operate only at night, only above clouds, and only when a star of sufficient brightness is in view.

Another proposal to use two satellites was investigated by IITRI. It called for on-board microwave radiometers to look at the same volume in the atmosphere, or area on the ground, to determine temperature, wind velocity, and water vapor concentration. According to this proposal, by observing the microwave emission characteristics of the volume at various absorption lines and by correlating the received signals at both satellites, information from the common viewing volume could be extracted, and the assumptions presently used to derive weighting functions and their attendant errors could be eliminated. It was decided, however, that many of the theoretical premises on which this proposal was based were in error and the concept would not produce the desired results. IITRI therefore recommended that further effort not be expended in this area.

# I. INTRODUCTION

Atmospheric pressure and density data are primary inputs to weather forecasting models. Proposals have been made to use co-orbiting mother/daughter satellites in the measurement of these parameters. If the satellites are properly spaced, radio transmission between them will pass through the atmosphere. It is a physical principle that the refractive index of the atmosphere is directly proportional to its mass density. Therefore, by measuring the effect of a changing refractive index on transmissions between mother/daughter satellites, it is possible to determine the corresponding change in mass density.

The earliest occultation studies were performed by observers on the earth's surface as means of studying the atmospheres of other bodies. In these cases, the effects of a planetary atmosphere or ionosphere on electromagnetic radiation from a star were measured. The measurements included the occultations of Arietis by Jupiter, of the Crab Nebula by the moon, and of Regulus by Venus. With the advent of the space age, the occultation technique was applied to the Mariner IV Mars flyby and Mariner V Venus flyby and significant data concerning the Venusian and Martian atmosphere and ionosphere were obtained. The major uncertainly in deducing from the Martian measurement the scale height (density and pressure variation) of the Martian atmosphere was in the constituent make-up of the atmospheric atomic weight. For the earth measurements the atomic weight is known to a very good accuracy.

An early suggestion to use a satellite for measurement of refraction on a continuous basis to determine atmospheric density and pressure appeared in 1962 in a report of the University of Michigan (ref. 3). In this and subsequent papers it was suggested that a satellite containing a telescope track a star as the star is occulted by the earth. Measurement of the apparent angular change in the position of the star would give an indication of the refraction of the portion of the atmosphere through which the starlight had passed.

In 1966, a letter by A. Werbowetzki (ref. 4) of ESSA modified the University of Michigan concept by calling for a mother and many daughter satellites. The waves from the mother to each daughter would cut the atmosphere at a different but known minimum altitude. Changes in atmospheric density along the path would appear as changes in the path length between satellites. Such an orbit would provide global coverage; all latitudes would be sampled twice each orbit while longitudinal variation would be achieved by the precession of the earth beneath the satellites.

At about the same time an interdisciplinary engineering course in Space Systems Engineering at Stanford University was investigating the meteorological needs of the world and potential methods of fulfilling these needs. The result of this investigation was the SPINMAP-Stanford Proposal for an International Network for Meteorological Analyses and Prediction (ref. 5). This report included a section calling for and analyzing a refraction-occultation satellite scheme similar to that of Werbowetzki. This has formed the basis for the work of Professor B. Lusignan of Stanford University in this field. His concept is discussed in detail in this report.

Also at about this time, Dr. Grossi of the Raytheon Company, Space and Information Sciences Division, became interested in the possibility of employing co-orbiting satellites around Mars or Venus to sample the atmosphere and ionosphere of these planets. Buoyed by the success of the Mariner IV occultation flyby, Raytheon undertook a study of the feasibility of putting two satellites into orbit around a planet to obtain information regarding its atmosphere, ionosphere, and surface characteristics over all longitudes and latitudes and over various sun conditions (day and night, quiet and active sun). In performing their study, Raytheon noticed that many of the same techniques could be applied to an earth-orbiting system. Thus, they included in their studies the possibility of obtaining measurements of the earth atmosphere and ionosphere. The concept subsequently developed is also described and evaluated in this report.

Characteristics of the occultation-refraction concepts are presented in Figure 1. Figure 2a shows the configuration of the Stanford system, while Figure 2b is the Raytheon configuration.

## II. METEOROLOGICAL REQUIREMENTS

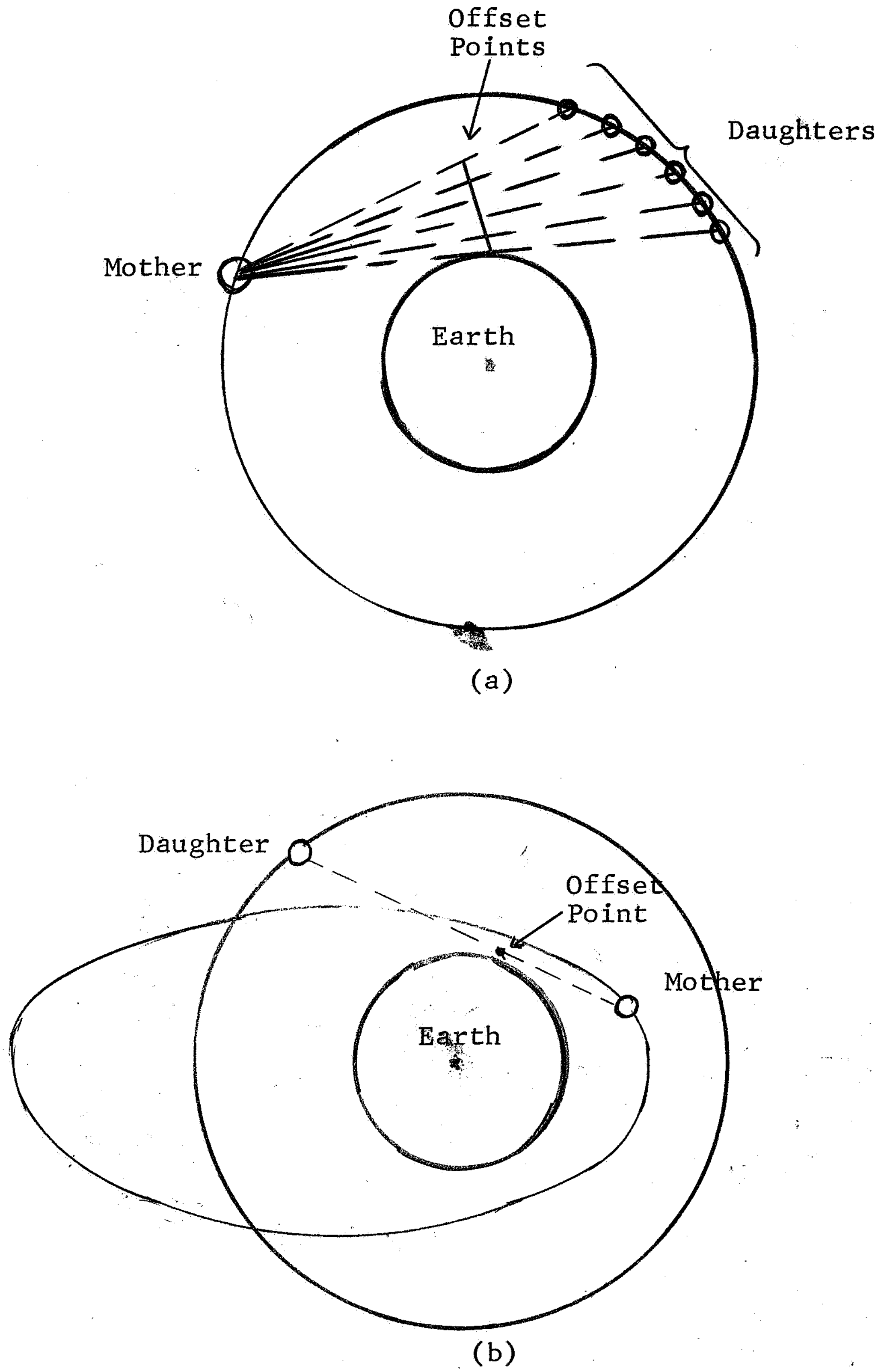
There is no one set of requirements for meteorological data in terms of accuracy and grid size. A number of mathematical numerical forecasting models are currently under development and the requirements of each are somewhat different. Also, at the moment, data are limited to those which are available from radiosonde balloons or other sparsely-concentrated measurement devices. The parameters of interest to meteorologists are usually wind velocity; temperature distribution (vertical and horizontal); humidity near the ground, in the troposphere, and in the stratosphere; and the height of isobaric surfaces (pressure levels).

A number of attempts have been made to define numerical accuracies for meteorological measurements. The WMO report by J.A. Sawyer (ref. 6) is only one such report. AGSTOMS (ref. 7) in 1965 developed the following set of requirements for balloon and other localized measurements.

## MULTI-SATELLITE REFRACTION TECHNIQUES

| Technique (Source) | Fischbach U. of Mich. | Werbpwetzki ESSA | Lusignan Stanford U. | Grossi Raytheon |
|---|---|---|---|---|
| Satellite Configuration | One satellite in circular, polar orbit | Mother, 8 daughters in circular, Polar orbit, one additional data relay satellite | Mother, 6 daughters in circular orbit. | 2 satellites-mother in eccentric polar orbit, daughter separated with velocity increment supplied at perigee of 600 ft/sec or 32.8 ft/sec. |
| Orbital Altitude | 1100 Km | 1000 Km | 1000 Km | 1000 Km perigee<br>2000 Km apogee |
| Measurement Technique | Star tracked by telescope as path passes through atmosphere angular change is measured of refraction | Differential in arrival time gives path length change. Model atmosphere matched to measurements. | Differential round-trip phase measurements give path length increase. Model atmosphere altered on iterative basis to provide true profile. | 2 frequency Doppler measurements, integrate to phase, converted to refractivity by model matching. |
| Stabilization Proposed | Gravity gradient | Spin | Gravity gradient | Not stated |
| Comments | Limited to above cloud height and nighttime operation | Variation of Lusignan technique | Readings taken at 5 distinct altitudes, continuous spacialty. | Readings taken continuously along a vertical, irregular spacialty. |

FIGURE 1



a) Stanford University Configuration (not to scale)
b) Raytheon Company Configuration (not to scale)
FIGURE 2

Horizontal: Measurements every 125 NM
Vertical: Measurements at the following levels:
From the surface to 500 mb, every 100 mb
From 500 mb to 100 mb, every 50 mb
From 100 mb, every 30 mb

Observations were requested every 6 hours. Pressure accuracies were to be to within 1 mb, or alternatively, heights to within (±) 30 meters.

At present there seems to be no economical way to achieve this global coverage without using satellites. It has been estimated that less than 20 percent of the earth's surface is adequately covered by upper-air observing stations (ref. 8). Numerical forecasts, treating the earth's atmosphere as a single dynamic system, are prepared routinely for periods of 3 to 4 days, and for areas covering about one-third of the earth. To extend forecasts to longer periods or to larger areas requires knowledge of the initial state of the atmosphere on a global or at least hemispheric scale. Otherwise, unknown disturbances will migrate into the prediction areas and contaminate the forecast.

Most prediction models require knowledge of the initial flow and mass distribution (density profile) of the atmosphere, and use primarily the height field of standard pressure surfaces. The customary way to obtain the mass distribution of the atmosphere is to measure, in situ, by radiosonde balloons, temperature as a function of pressure and to integrate upward from the surface to obtain pressure as a function of height.

In planning a density or pressure measuring system, one must know the expected variations encountered in the course of an orbit and from orbit to orbit. The U.S. Standard Atmosphere, 1962 (ref. 9) and U.S. Standard Atmosphere Supplements, 1966 (ref. 10) have a large amount of information, containing detailed density, temperature and pressure data for the U.S. from the surface to well above altitudes of direct interest to meteorologists.

## III. SPECIFIC OCCULTATION-REFRACTION TECHNIQUES

It has long been known that electromagnetic waves are refracted when passing through a medium of changing refractive index. One is familiar with the appearance of a spoon in a glass of water or the sun at sunrise and sunset as examples of this phenomenon. Radio waves exhibit the same effect. Thus, transmission beyond the line of sight (geometrical straight line path) is possible as the rays follow to some extent the curvature of the earth.

Transmissions at frequencies in the VHF and UHF ranges are affected by the ionosphere. Ionospheric bending is usually opposite to atmospheric bending, however. Thus, rays subject to ionospheric refraction will bend away from the earth. The effect of the ionosphere decreases with increasing frequency, contributing 2.3 m to the path length of a grazing ray at 5 GHz. It is not easy to separate the ionospheric and atmospheric effects if the frequency chosen is too low; at too high a frequency equipment and signal intensity problems are present. Higher frequencies are also subject to greater attenuation by rain and clouds. The choice of frequency for atmospheric measurements is thus limited to near 5 GHz. It may be noted that the refractivity of the atmosphere itself is only very slightly a function of frequency. Therefore, the selection of frequency is not governed by refractivity considerations.

## IV. STANFORD TECHNIQUE

The orbital configuration proposed by Stanford University for an operational system is shown in Figure 2a. It consists of a mother and 6 daughter satellites in the same circular polar orbit of approximately 1000 km altitude. The spacing between the satellites will be fixed. The path between the mother and closest daughter satellite will always be above the atmosphere, providing a measure of the gravitational effects on the orbits while the other paths will cut through the atmosphere at various levels giving a vertical profile for density.

In operation, the mother would transmit a 5 GHz wave, phase modulated at 3 MHz, to each daughter. The daughter would receive the signal, shift frequency slightly, and retransmit it phase coherently back to the mother. At the mother, the received signal from the daughter is compared with the transmitted signal to determine radio path length and rate of change between the satellites. The carrier comparison would be in terms of frequency (Doppler) shift caused by changes in the radio path length, giving range rate, while the modulated signal comparison would be in terms of the difference in phase of the received and transmitted signals giving radio distance. At a frequency of 5 GHz, each wave-length is 6 cm long; measuring range rate on the two way path to one Hertz provides a minimum sensitivity of 3 cm/sec. The absolute value of path length, if the phase of the modulated signal can be measured to 4°, will be known to 1/2 meter on the one-way path, with an ambiguity or uncertainty of a hundred meters (one wavelength of the modulating wave).

The link between the mother and closest daughter in the Stanford system will be used to measure the orbital perturbations since the rays on this link will not pass through the atmosphere. The satellites will have a relative motion due to three causes: (1) orbital eccentricity, (2) the oblateness of the earth, and (3) small differences in the orbital period. Stanford is optimistic that corrections for the relative velocity can be made from long-term tracking analysis and use of measurements on the mother-first daughter link.

As the rays from the mother to the 2nd through 6th daughter pass through the atmosphere, they are subjected to an increasing index of refraction until reaching the point at which they are at their minimum altitude above the earth's surface. This point, the offset point, is taken to be the point at which the refraction is being measured. Stanford's computer calculations have shown that 75 percent of the bending and retardation occurs over a horizontal distance of 500 Km, or between the earth's surface and 10 Km altitude for a ray tangent to the surface at its offset point. Thus, for each measurement, the Stanford University technique yields an average of the atmospheric refractivity over a horizontal length of 500 Km. Fresnel zone calculations indicate a horizontal dimension of about 1.3 Km and a vertical dimension of about 1 meter. Rays reaching the receiver from paths outside this zone will be out of phase with the direct ray and will not contribute to the measurement.

## V. RAYTHEON TECHNIQUE

The experimental concept developed by the Raytheon Company for sensing the atmosphere and ionosphere employs only two satellites. However, these satellites are placed in different orbits; the orbit of the mother is elliptical and the orbit of the daughter is circular. In this configuration the satellites will continuously approach and separate from each other. The offset point, which is the point of minimum altitude of the ray between the satellites, will thus vary continuously, moving from about 1000 Km to the earth's surface. This is shown in Figure 2b.

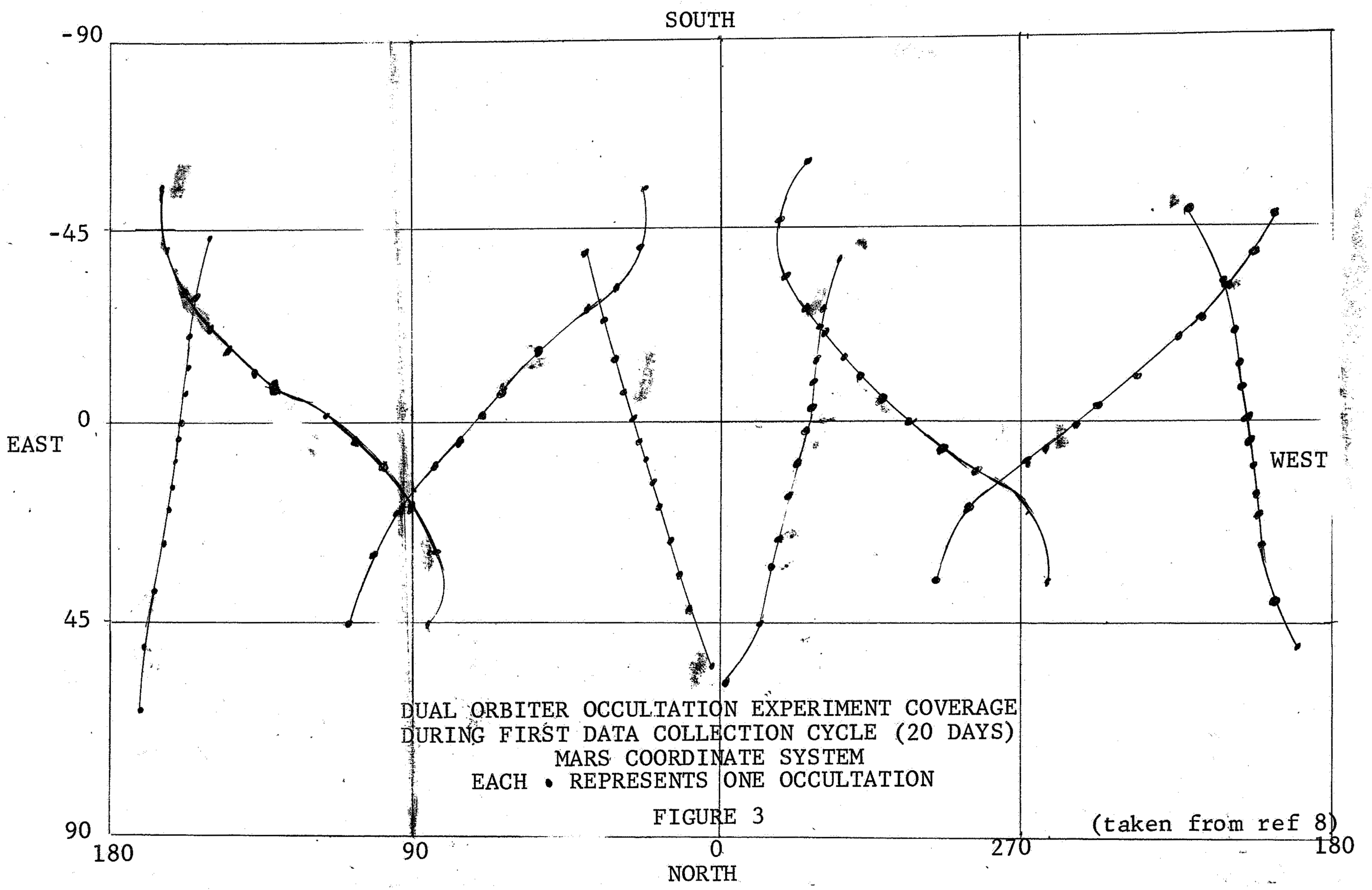
Raytheon's analysis concluded the proper orbits to be such that the satellites will separate or approach each other at a rate which moves the offset point vertically at 1 Km/sec. The atmosphere from the earth's surface to 30 Km will therefore be sampled in 30 seconds and, if each sampling period is 1 second, averaging is over a vertical grid size of 1 Km. In 30 seconds, the satellites will travel about 150 miles along the surface of the earth, assuming a velocity of 5 mi/sec.

The measurement technique for this configuration is identical to the one used on the Mariner IV and V probes. Doppler shift of signals between the satellites is the parameter of interest. While the offset point is above the atmosphere, all Doppler is geometrical, caused by the relative velocity of the satellites. When the ray enters the atmosphere, additional phase shift will be registered. Measurement of this additional phase shift due to the atmosphere is the first step in determining the profile.

The geometrical Doppler must be accurately determined to avoid contamination of the results. At present, Raytheon asserts that range rate can be determined to within 1.5 cm/sec. but their goal is 0.1 - 0.2 cm/sec. The method suggested to determine the geometrical range rate is to extrapolate the accurate extra-atmospheric range-rate data, which was taken when the ray was above the atmosphere, to the period of measurement.

To provide regular, global coverage many such satellite pairs would be required. The coverage from one pair would be spotty and irregular. Raytheon has computed the coverage pattern for Martian co-orbiters. Figure 3 shows the location of occultations on Mars over a 20 day period (ref. 11).

Other orbits may prove to be more advantageous to an operational system. One possibility mentioned puts the mother satellite into an inclined synchronous orbit with a number of daughters flying in lower circular orbits. This aspect of the proposal requires further study. The particular orbits themselves however, are random in nature and the coverage of the system would not be severely imparied if a slight amount of drift should occur in one or both of the satellites. This reduces or possibly eliminates the need for station-keeping on board the satellites.



DUAL ORBITER OCCULTATION EXPERIMENT COVERAGE
DURING FIRST DATA COLLECTION CYCLE (20 DAYS)
MARS COORDINATE SYSTEM
EACH • REPRESENTS ONE OCCULTATION

FIGURE 3

(taken from ref 8)

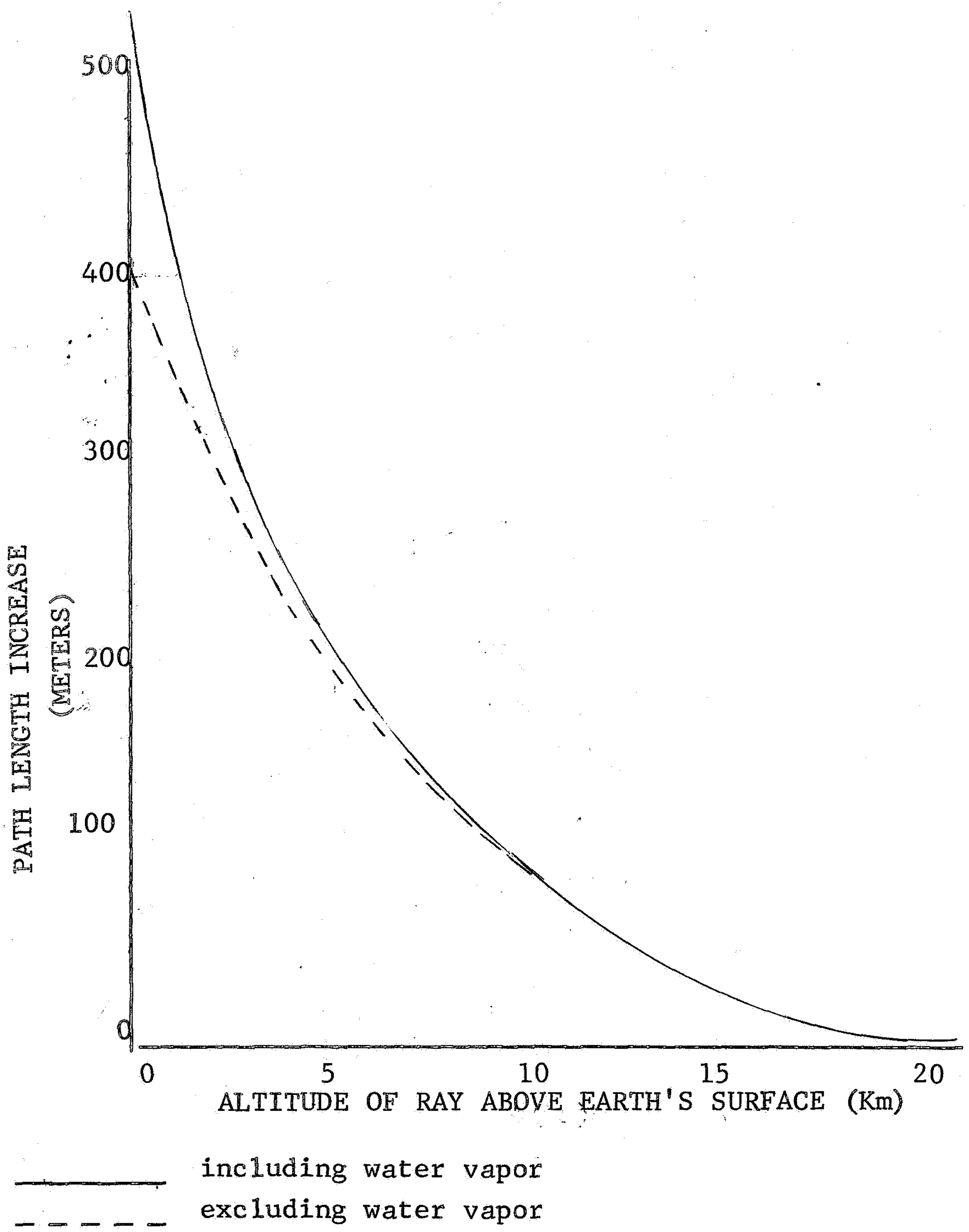
# VI. ANALYSIS

## A. Water Vapor Problem

The Stanford and Raytheon concepts share many features. The basic measurement techniques are quite similar, and the influence of anomolies in the atmospheric structure is the same. In performing an analysis of the concepts, certain areas of difficulty appear common to both, while others affect one more than the other.

Accounting for water vapor in the lower atmosphere is one of the most serious difficulties encountered by the refraction-occultation technique. At the earth's surface, the refractive index is on the order of 300 N units with perhaps 60 N units contributed by the water vapor. According to Professor Lusignan, knowledge of water vapor to 1 percent is necessary to determine atmospheric density at the 800 mb level. Above this level, less accuracy is needed since water vapor decreases exponentially with height. Above about 10 Km, water vapor is no longer a problem. Figure 4 shows the differential path length increase, with and without water vapor as a function of altitude.

A number of methods were investigated by IITRI for measuring water vapor. These include carrier amplitude, IR and microwave radiometry, low-altitude refraction measurements, and dispersion. Measurement of carrier amplitude as the primary technique is very delicate. Carrier amplitude measurements may be useful since water vapor has a greater attenuation on the signals at 5 GHz than the dry atmosphere does. However, the sensitivity



PATH LENGTH INCREASE VS ALTITUDE

FIGURE 4

is even greater at higher frequencies. A more reasonable suggestion, it seems, is to measure the signal amplitude at a frequency closer to the 22 GHz absorption line. The optimum frequency is yet to be determined. One too close to the absorption line will over-attenuate the signal and one too far removed will not have the required sensitivity.

Radiometry is now becoming a useful tool to meteorologists. Microwave radiometers would be preferred since water vapor measurements close to the surface are required and IR sensors cannot penetrate clouds. At present, considerable effort in microwave radiometry is being given to temperature measurement utilizing the 60 GHz $0_2$ line. Some successes have been reported. IITRI feels that, in the near future, given proper encouragement, water vapor measuring microwave radiometers could be perfected and could prove to be quite helpful in acquiring the needed data.

Since the refraction measurements at altitudes below 800 mb are more sensitive to changes in water vapor than density, it has been proposed that these low altitude measurements be used to construct a water vapor model. It is the opinion of IITRI that this is a roundabout way of getting the desired information and that any errors in the water vapor profile derived in this way would be magnified when the density profile is computed.

The dispersion technique uses the physical characteristic that the refraction due to water vapor is a slight function of frequency. The Mitre Corporation, (refs. 12, 13) in 1965, experimented with measuring the magnitude of the dispersion and concluded that by making measurements at two fairly separate frequencies (15 and 30 GHz) simultaneously and monitoring the differential frequency shift between the signals, it was possible to determine the average humidity along the path. This technique needs more testing but holds promise if it can be demonstrated to work successfully in space and if the high frequencies required can be used without requiring excessive satellite power.

### B. Orbital Prediction Problem

Another vital area for the refraction-occultation operation is in the orbital prediction accuracy needed. The Stanford experiment calls for the accurate measurement of inter-satellite distance by radio means and the calculation of the difference between that value and the true value. Both techniques require precise tracking for offset-point determination. If bending is not considered, a fifty meter error in the altitude of one satellite of a satellite pair will cause about an 18 meter error in the altitude of the offset point. A fifty meter error in the altitude of both satellites in the same direction causes an error in the offset point altitude of about 43 meters. For 1 and 3 mb pressure accuracies, height accuracies of 10 m and 40 m are required at the 800 mb level. Consequently, offset-point accuracies to 30-50 meters will be required in the operational system.

At present, satellite orbits can be predicted to within about 100 meters with a fair amount of post-tracking analysis. On the basis of conversations with scientists in the field, such as Dr. Joseph Siry of Goddard Space Flight Center (ref. 14) and Mr. Roger Easton of the Naval Research Laboratory (ref. 15), the necessary improvements will require a significant expenditure in funds for additional tracking stations as well as further development of analysis techniques. Hence, orbital prediction, particularly in a relatively real-time mode, may prove to be a limiting consideration. Station-keeping will be required for the Stanford configuration, but not for Raytheon.

## C. Atmospheric Anomaly Problem

Another difficulty associated with the calculation of the offset point altitude is the uncertainty of the physical atmosphere being sampled. As stated above, the refraction is an average over about 500 Km. Any fronts or severe gradients within this average will influence the measurement but may not be detected as sharp discontinuities. However, it may turn out that fronts will become detectable since they may show up gradually in the measurements, having a different influence on each successive measurement depending on the nature of the front. This question may only be answerable after experience has been obtained with satellite measurements and these measurements have been related to other readings taken conventionally.

The presence of ducts in the atmosphere may also lead to errors, both in the phase path length being measured and in the location of the offset point. If the ray is trapped by a duct, its path is no longer the shortest in time through the atmosphere, but may be considerably longer. The existence of ducting of 5 GHz signals has been confirmed, but the statistics of occurrence are not well known. Experience has shown that as the frequency is raised the amount of ducting is less, especially in the microwave region. Further investigation is needed in terms of frequency of occurrence and radio-frequency dependence of ducts. Perhaps by choosing the frequency carefully, or even using two frequencies separated by a significant amount, the effects of ducting can be made negligible. Other difficulties may occur in the areas of multi-path and scintillation.

Reception of two rays at the daughter satellite, one directly from the mother satellite and the other reflected from the earth's surface, can cause errors in the phase shift measured by the daughter. The magnitude of this effect was calculated for the cases of direct rays 1 Km and 10 Km above the earth's surface at the minimum altitude point of the ray. The phase error in the first case was 2.7° and in the second was 27°. At 1 Km height the error is within experimental accuracy, while at 10 Km, the amplitude of the reflected ray may be reduced and its effects are of less concern.

Scintillation is the rapid increase or decrease in signal intensity due to atmospheric stratification or ducting. It probably will not be a severe problem for operation at these frequencies:

"At some frequencies, the intensity of signals received from discrete sources is not steady but exhibits fluctuations or scintillations. Fluctuations in the microwave region are of long periods and seem to originate in the troposphere. In general, the number and amplitude of the scintillations vary inversely with some power of the frequency; scintillations at high frequencies are much less noticeable than at lower frequencies" (ref. 16).

## D. Inversion Computation Problem

The general technique for determining atmospheric density and pressure from path length and phase shift measurements as developed by Professor Lusignan is shown in Figure 5. Dr. Grossi's method is quite similar. In brief, a model atmosphere, including pressure, density, water vapor and temperature, is assumed, extending from the earth's surface to the maximum height of interest, about 30 Km. The refraction data from the link containing the highest offset point is considered first. This value of differential path length is compared with the theoretical value that is calculated from the assumed atmosphere. The model is changed until agreement with the measured value is reached. Thus, the density from the offset point to the effective top of the atmosphere is determined.

The data from the next link, in Professor Lusignan's configuration, or from the next reading, in Dr. Grossi's configuration, is considered. The assumptions comprising the model are again modified until the calculated and measured values of differential path length agree. After modification the density from this offset point to the previous one is thus determined.

## STANFORD INVERSION

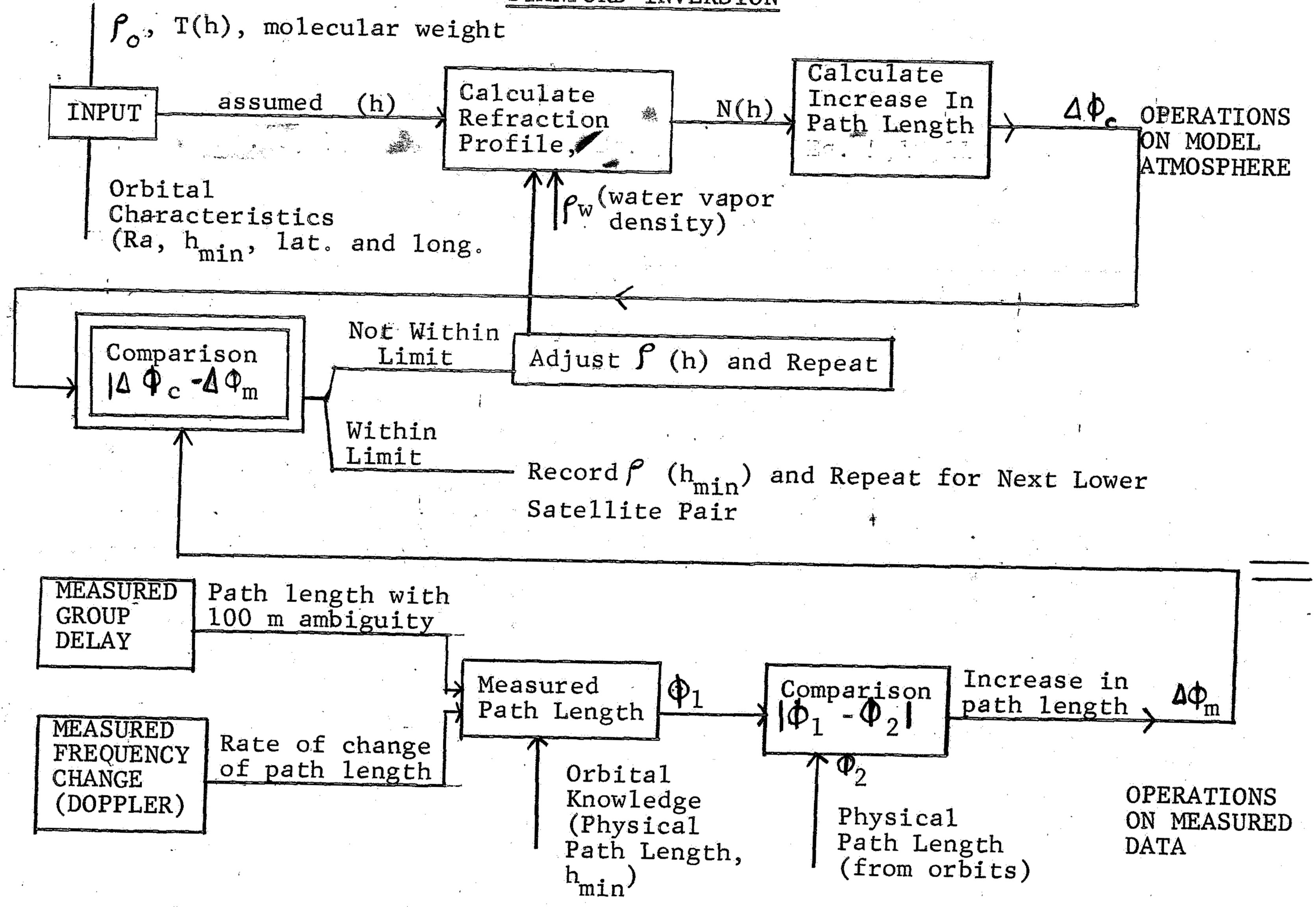


FIGURE 5

Each lower link is considered in sequence, in the same manner, until the density to the earth's surface is determined.

Theoretical calculations of differential path length by Professor Lusignan and Dr. Grossi exhibit a discrepancy of a factor of about 2 or 3. Professor Lusignan computes a maximum path length increase for a tangent ray of approximately 530 m, while Dr. Grossi computes one of approximately 170 m for the same ray. The reasons for the discrepancy are not clear, but may be due to different atmospheric assumptions. Further numerical sensitivity calculations should be made by both Lusignan and Grossi to improve their computer programs and to establish more precisely the impact of theoretical and experimental inaccuracies.

As mentioned above, there are many inputs to the data inversion and processing. The exact satellite locations and the water vapor and temperature profiles are the most important items that must be obtained independently of the Doppler-shift data. By including additional instrumentation the latter two problems may be solved. Multiple frequency sensors may provide the required water vapor measurement and infrared vertical sounding sensors may provide the required temperature measurements.

It should be recognized that the refraction-occultation scheme will be but one contributor to the meteorologists's input data. By itself it will not provide all the meteorological information required but by providing global density profiles it will bridge a large gap. No other technique to date has shown promise of doing this. Consquently, it is recommended that additional funding be provided for both theoretical research and field measurements.

## VII . MICROWAVE CORRELATION CONCEPT

A suggestion was made at the National Academy of Sciences 1967 Space Applications Summer Study to use co-orbiting satellites to measure atmospheric temperature, wind velocity, and water vapor. Microwave radiometers, operating at the oxygen and water vapor absorption lines, would be placed aboard two satellites. The satellites were to be separated by about their altitude but in the same circular orbit. Both radiometers would view the same volume in the atmosphere, or area on the ground, but from different angles. It was hoped that by correlating the output from the radiometers, the noise from the common volume could be extracted from the total noise received and information about this volume could be inferred.

On the basis of a theoretical analysis, IITRI concluded that this particular concept was not feasible for a number of reasons. First, the level of signal emanating from the common volume compared to the received noise level is not large enough to permit correlation detection. Second, the spontaneous emission from the common volume is highly directional; thus, the noise emanating from the common volume will not correlate, even with an adequate level. Third, the station-keeping and attitude control requirements are beyond the state-of-the-art. Therefore, IITRI recommended that no further effort be expended on this specific application.

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