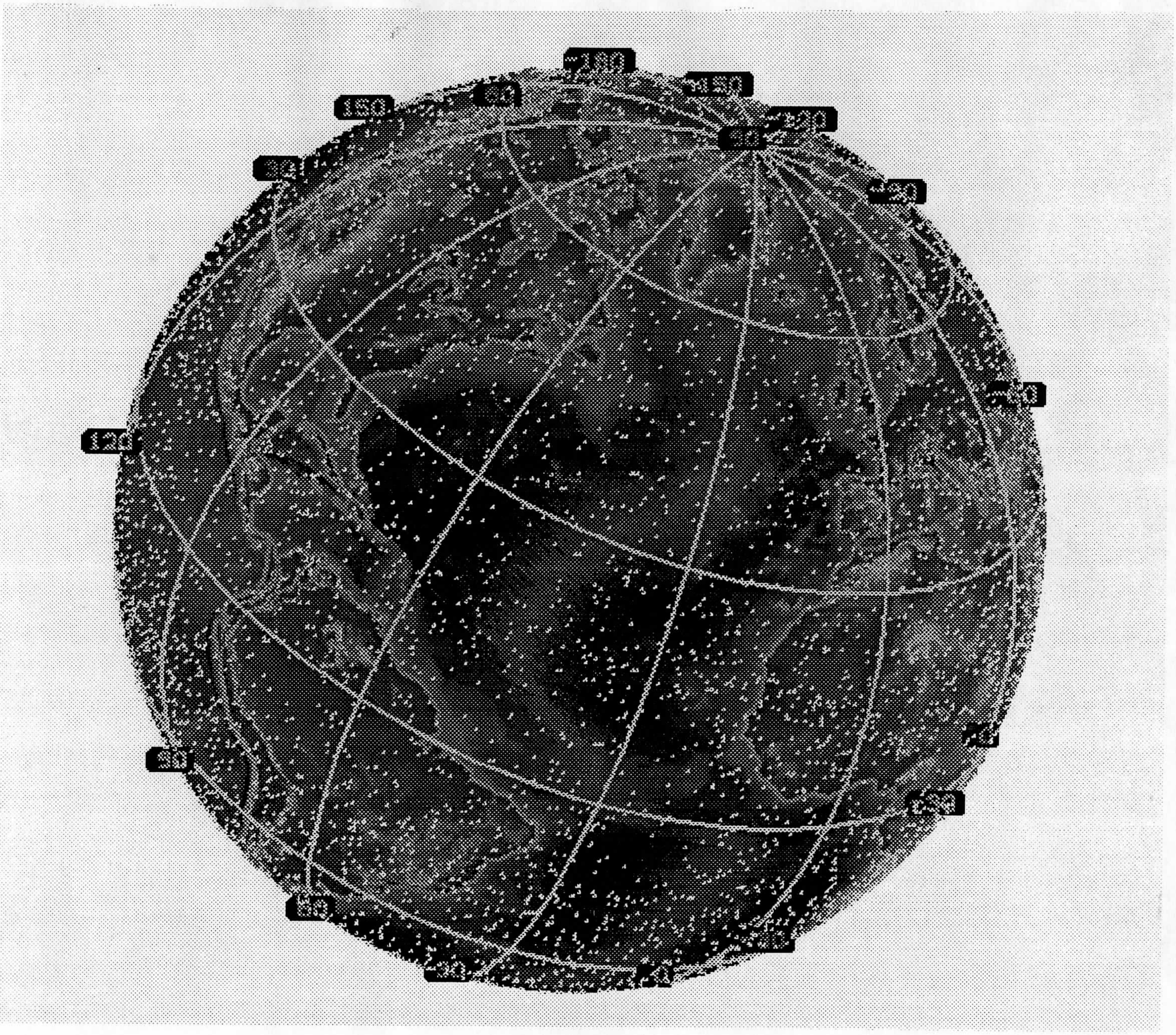
Final Report

# INVESTIGATION OF GLOBALSTAR PIGGY BACK PAYLOADS



prepared for Space Systems/Loral, Inc. under Contract KS-274640-B

by

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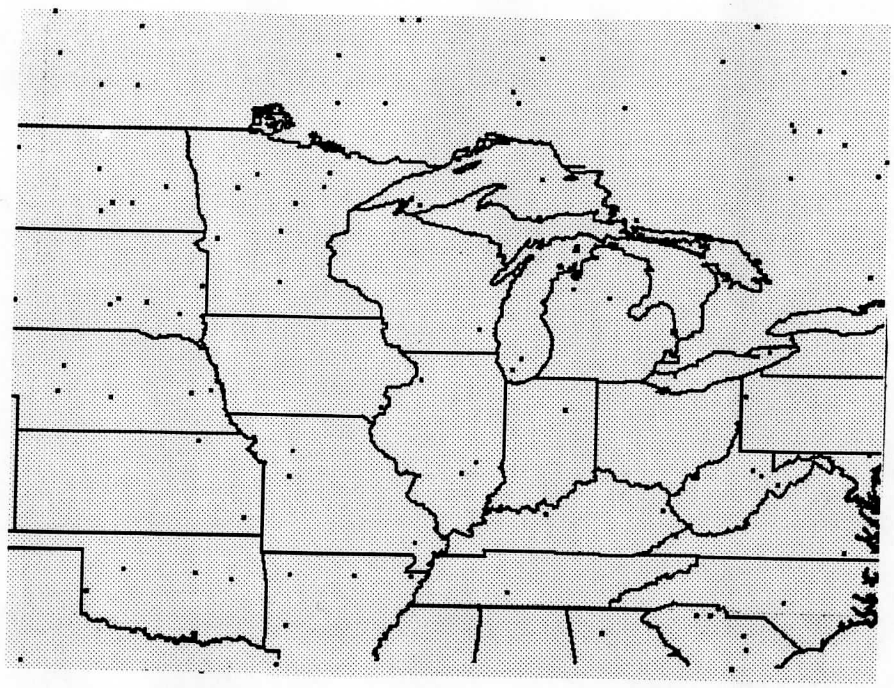

**Cover Picture:** The dots in the cover picture are the geographic locations of the occultations between the 48 Globalstar satellites with one GPS satellite in 24 hours. To visualize the occultations occurring with the projected final GPS configuration of 24 satellites would require 24 times as many "occultation dots" on the image, which makes the image practically illegible. Stated another way, there are nearly 1,000 occultations per hour between the 48 Globalstar and 24 GPS satellites in the planned configuration, or over 20,000 occultations per day.

This picture illustrates, more graphically than any words that we can conjure up, the outstanding value as a global sensing platform for geophysical observations of a combined Globalstar - GPS system. Picture each of these points as the location of a vertical profile of the atmosphere's density (and therefore winds) and water vapor, and the system's value as an input to numerical analyses and models is self-evident.

In the picture, the earth's image is tilted so that the north pole is clearly visible. Note the relatively uniform distribution of occultations except within two degrees longitude of the pole. This superb coverage beats anything previously considered as a global observing system by a wide margin, both temporally and geographically. Pictures of this nature should be very useful in selling the concept to governments.

**Picture Above:** To warn against the impression that there may be more observations than necessary, and that perhaps it is not essential to instrument all of the Globalstar fleet, we show above a map outline of the midwestern United States under the same Globalstar - GPS circumstances as the earth disk portrayed in the cover picture. The occultation coverage (shown by the dots) is roughly equivalent to the present radiosonde (balloon) network over this area. We thus strongly advocate that all Globalstar satellites be instrumented to obtain the superb geographic coverage shown in the cover picture. Such superb coverage is essential to current and proposed weather and climate models.

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# Executive Summary

Suomi Scientific, Inc. (SSI) investigated three candidate secondary payloads for the Globalstar satellite system. These three candidate payloads were to:

1. Determine the atmospheric density profile by measuring the retardation of GPS signals during occultation.

2. Measure the atmospheric moisture using a Ka-band beacon on a selected number of Globalstar satellites.

3. Measure ozone in the atmosphere using a selected frequency beacon on a selected number of Globalstar satellites.

With respect to these potential payloads, SSI concludes that:

1. Atmospheric density (and therefore atmospheric winds) by occultation measurements appears very promising. Definitive modeling should show that the results are much better than we first expected. Indeed, when used in combination with the moisture sounding option described below, we can expect to produce usable density soundings to near the surface even in the moist tropics. Even though the GPS - Globalstar occultation paths are different than the Globalstar - Globalstar paths, a mathematical model can assimilate these different data to provide an improved picture of the tropical winds to a lower altitude than with either type of data alone.

   A fully coded GPS receiver on a Globalstar satellite receiving three unobstructed GPS satellite signals will give the Globalstar satellite's latitude, longitude and ALTITUDE to a meter or less for each second. Another GPS satellite, whose signals are being occulted by the atmosphere, will give a false position compared to the position derived from the other three. The false position is caused by the signal delay, which is in turn caused by the average density of the atmosphere in the occulting path. The difference of these two positions is the information we are after. If codes are not available, an alternate scheme using a second Globalstar satellite as a relay can provide equivalent performance.

   The change in pressure with altitude is given by $dp = -g\rho dz$, where $\rho$ is the atmospheric density, p the pressure, g the acceleration of gravity, and z is the height. To obtain the pressure at a given height, one integrates the expression from zero pressure to the height of interest. If one has the global pressure distribution as a function of height, one knows the slopes of the constant pressure surfaces and, *voila*, one knows the winds as a function of height all over the globe where there is little water vapor, usually at heights above 5 km or at cold latitudes. THIS IS A COMMERCIALLY VALUABLE PRODUCT FOR THE AIRLINE INDUSTRY OVER THE PACIFIC AND THE SOUTHERN HEMISPHERE, AS WELL AS GENERAL AVIATION OVER THE UNITED STATES. Any pilot, and especially the private pilot, can then get his winds by telephone in near real time.

   It also follows from the equation of state that high precision global vertical profiles of the index of refraction and the temperature can be derived from the density and pressure distributions where the air is dry, i.e., $T = p/\rho R_d$, where $R_d$ is the gas constant for dry air.

2. Atmospheric water vapor measurements by absorption in the microwave portion of the spectrum are quite feasible by two methods. In the first method, presently typified by the SSMI sensor, the total water vapor in a column is obtained over the ocean using the 22.4 Ghz microwave emission from the atmosphere's water vapor. At this frequency, the ocean appears cold because it acts like a mirror, so that the observed background is near the sky temperature. The land surface is a poor reflector

(good emitter), so one cannot see the colder water vapor against the warm background. The beacon system being proposed for land surface observation from Globalstar satellites provides three microwave signals which straddle the 22.4 Ghz water vapor band. Receivers on the earth's surface (ground or ocean) are thus looking at a cold sky background, and so give excellent total water vapor observations, even better than the SSMI observations. Using the store and forward capability mentioned below, observations taken while out of range of a gateway station can be retained and forwarded to the next gateway station contacted, thus yielding global water vapor observations over all lands and also from moored or drifting buoys which might be part of the Global Ocean Observing System (GOOS) of the future. *Voila* again!

A second water vapor measurement method makes use of occultations between sister Globalstar satellites equipped with 22.4 Ghz transmitters and receivers in the bands mentioned earlier. Here, the water vapor measurements are not only much better (because of the much longer optical path), but during an occultation sequence one gets both the TEMPERATURE and WATER VAPOR SEPARATELY as functions of height. A very loud *voila* again. Unfortunately, the Globalstar sister to sister occultations are oriented along latitude bands and the global coverage for winds is not as good as the GPS to Globalstar occultations. However, the combination of the two systems is very powerful and can be used to provide the water vapor transport from the tropics to higher latitudes, a key set of observations for long range weather forecasts, climate and GEWEX, the Global Energy and Water Experiment beginning in the late nineties, about the same time Globalstar satellites are to be launched. The GEWEX experiment is THE major international meteorological program for the next decade and a Globalstar moisture capability could play a major role in the program.

3. Ozone determination using absorption techniques for a Globalstar beacon does not appear feasible because the total amount of ozone is so low, even on occultation paths.

While discussing the first draft of this report with SS/Loral, SSI learned that SS/Loral is contemplating the use of data storage onboard the Globalstar satellites to acquire data from global locations that are out of range of gateway stations. While the time delay induced by onboard storage of information is unacceptable for telephonic communication needs, it is perfectly acceptable for meteorological data needs. After all, a radiosonde balloon sounding requires up to two hours to complete, but the time of the observation is considered to be the balloon launch time.

The implications of this store and forward capability are enormous. While we have not had an opportunity to study this possibility in detail, we know enough to see its implications for all meteorological and oceanic data. Real time data for meteorology and oceanography (with some notable exceptions such as lightning) is considered real time if it is within 30 minutes or so!

These new observing opportunities represent a quantum leap in our ability to observe the global atmosphere. These advantages exist both for weather and climate purposes over what we have now. However, realizing immediate economic benefits in the marketplace may be fraught with hazards, as the most likely customer is the U. S. Government. Lesser markets exist in the near term in the non-governmental sector, and have great potential for the long term future, but will require lots of nurturing to bring to fruition. One possibility is the store and forward meteorology and ocean data systems impact on the World Weather Watch's present communication trunk system, which is expensive and slow. In this regard, Globalstar's greatly improved data collection scheme definitely warrants further study. It could include things measured from the surface as well as things measured from the sky. It has tremendous potential for weather and climate, and for SS/Loral's corporate income.

**Final Report**
**Space Systems/Loral, Inc. Contract KS-274640-B**

# INVESTIGATION OF GLOBALSTAR PIGGY BACK PAYLOADS

## I. INTRODUCTION

Space Systems/Loral, Inc. (SS/Loral) tasked Suomi Scientific, Inc. (SSI) under SS/Loral contract KS-274640-B, to perform specialist support in the definition of three candidate secondary payloads for the Globalstar satellite system. The purposes of these three candidate payloads were:

- Determine the atmospheric density profile by measuring GPS signal retardation during occultation.
- Measure atmospheric moisture using a Ka-band beacon on a selection of Globalstar satellites.
- Measure ozone in the atmosphere using a selected frequency beacon on a selected number of Globalstar satellites.

This report contains the results of SSI's studies as orally presented to SS/Loral in Palo Alto on 17 and 18 March 1993. It's organization follows that of the three candidate payloads listed above. First, we will look at atmospheric observations obtainable through radio occultation measurements made using various constellations of Globalstar and GPS satellites; second, we examine the measurement of atmospheric moisture through microwave (Ka-band) absorption measurements between the Globalstar satellite and the ground as well as between sister Globalstar satellites, and third, we examine the feasibility of determining ozone concentrations through beacon absorption techniques. Finally, we include some additional related information that is not part of the work statement.

## II. MEASURING ATMOSPHERIC DENSITY USING RADIO OCCULTATION TECHNIQUES

We examined four system geometries to measure the atmospheric density using radio occultation techniques. Each configuration requires modifying the Globalstar satellites to receive the GPS signals.

### A. Theoretical Considerations

The GPS is a very precise navigation system which, when completed, will consist of 24 operational satellites in 20,000 km altitude, 12-hour circular orbits. They are arranged four each in six equally spaced orbital planes inclined 55 degrees to the equator. Nineteen of these GPS satellites are currently in operation. Furthermore, the U. S. Government has issued a policy statement inviting international use of the GPS with no user fees for at least the next ten years.

Each GPS satellite carries an extremely accurate clock and accurate position information for each time interval. When signals are decoded completely, very accurate navigational positions can be obtained. The results are so good that for purposes of national security, the precise codes needed for the highest accuracy ranging are restricted.

The basic scheme is to measure the atmosphere-induced delay in the propagation of the signals emitted by the GPS satellites as they are received by modified Globalstar satellites. All GPS signals received on the earth are modified by passage through the earth's atmosphere to some extent. However, when the signals to one satellite are much more delayed by passage through the earth's atmosphere during occultation, it is possible to observe the vertical structure of the index of refraction of the atmosphere, and from that, to calculate the temperature structure at altitudes above 5 km. At altitudes below 5 km, the effect of water vapor on the index of refraction is a large factor and must be removed using an estimate or a measurement of the water vapor content for the purpose of temperature profile determination. Alternatively, given a temperature profile estimate, the water vapor profile in the lower troposphere could be determined from the occultation measurement.

## B. Geometries for Occultation Measurements

In the initial phase of this study we identified and explored four basic configurations for radio occultation measurements of atmospheric temperature and moisture. These configurations spanned a wide range of complexity and performance with the measurement capabilities ranging from regional measurements of refractive index to separate, global measurements of temperature and moisture. Specifically:

1. In option 1 a Globalstar satellite equipped with a Y-code receiver uses three or more unobscured GPS spacecraft to determine its precise position and time. A fourth GPS satellite which is being occulted is then ranged using the coded transmission and the excess path delay associated with the atmosphere is directly measured. The spacecraft hardware consists of a suitably modified precision GPS receiver and the hardware necessary for code distribution and reception. This option measures only refractive index. (See Figure II.1)

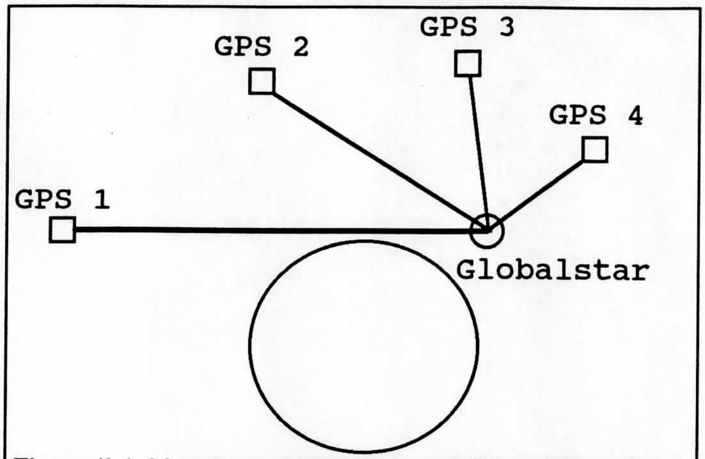


Figure II.1 Y-code receiver equipped Globalstar using 3 or more unobscured GPS spacecraft to determine position and time while ranging the GPS being occulted.

2. The second option involves the simultaneous observation of a single GPS transmitter by a Globalstar satellite through an occulted path and a reference ground station which will be used to make differential measurements of the atmospheric delay. The use of differential measurements eliminates the need for the GPS selective availability code; however, the system is far from simple since there are two receiver delays as well as a downlink path to be characterized. In addition, the system does not make truly global measurements. This option measures only refractive index. (See Figure II.2)

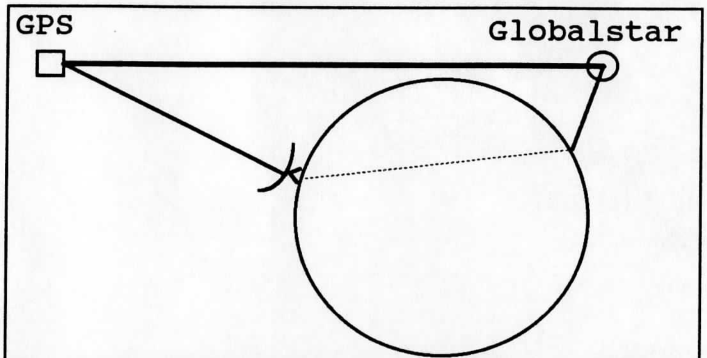


Figure II.2. Observation of a single GPS by Globalstar with reference GPS signals provided by a precisely located ground station.

3. Option 3 is very similar to option 2 except that the ground based GPS reference station is replaced by a non-obscured relay path from the GPS satellite to the Globalstar spacecraft trailing in the same orbit plane to the Globalstar satellite that is observing the GPS occultation. In this way, the need for the SA codes is eliminated without incurring a second atmospheric path or compromising the global observation coverage. The hardware needed for this option is a fairly simple cross-link between the receiving Globalstar and the trailing relay satellite. This link can be at any convenient frequency and the geometry is fixed so that a steerable antenna is not needed. (See Figure II.3)

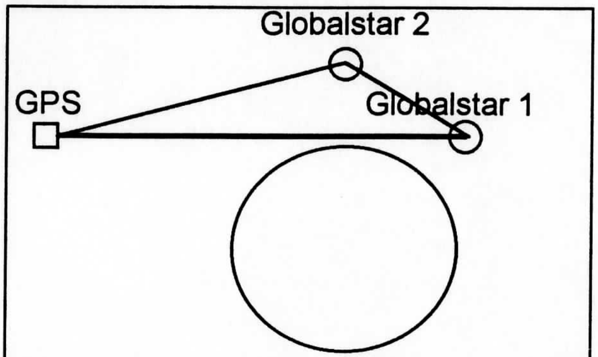


Figure II.3. Observation of an occulted GPS with reference provided by relay through trailing Globalstar in the same orbit plane.

4. The final option involves replacing the GPS to Globalstar occultation with a Globalstar-Globalstar occultation path between satellites in different orbital planes. The principal advantage of this option is that the occultation frequency can be chosen to include a signal in the 22 GHz water resonance so that the additional path delay due to water vapor can be separated from the delay due to the density of dry air alone. This option can thus make separate global observations of humidity and density, a very large advantage. The additional complexity associated with this option lies in the fact that the cross-link is now the occultation link. The cross-link must be in the Ka band so that observations of the water resonance can be made and, due to the reduced effective area of the antennas at Ka band, both satellites will have to use fully steerable high gain antennas. The timing for the occultation measurements can be provided by either carrying ultra-stable oscillators on both satellites or by both satellites using a non-occulted GPS transmitter as a time reference. (See Figure II.4)

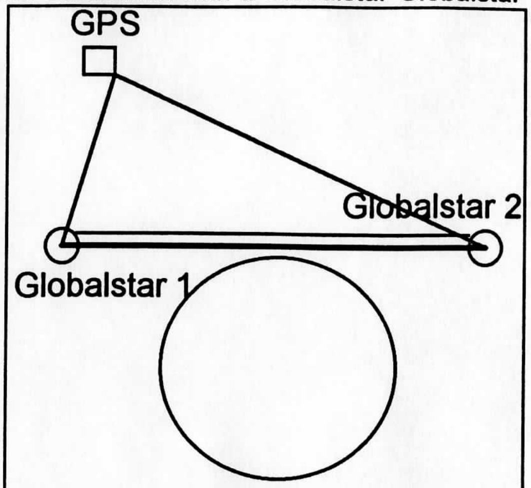

Figure II.4. Globalstar to Globalstar occulted path with additional cross-link between Globalstar satellites.

After our initial review of system configurations, we eliminated options 2 and 4 from further consideration. Option 2 was eliminated because it does not provide true global coverage and we felt that the complexity of the link to the ground based reference station was at least as hard as the simple cross-link needed in option 3. Option 4 was eliminated since the need for steerable Ka band cross-link antennas did not seem compatible with the baseline requirements for minimal impact to the Globalstar spacecraft. However, we looked at a limited version of option 4 which would provide water vapor at a limited number of latitudes and require non-steerable antennas on a small number of Globalstar satellites. This suboption is discussed in section II.D and has the potential for providing a very exciting product for use by the atmospheric science and climate community studying the transport of water vapor.

Appendix 1 documents some of the geometrical considerations reviewed, the orbital elements assumed for our studies of the coverages and frequencies of occultation of the various constellations, and some conclusions and insights drawn from this work.

The choice between options 1 and 3 is a purely technical and operational one. These two surviving options have nearly exactly the same performance and measurement characteristics since they have the same occultation path geometry - the only relevant question is whether the additional hardware required for a simple non-steerable cross-link is more expensive than the costs associated with the coded GPS receiver and the associated code distribution system.

## C. Signal Processing and Data Volume Issues

Occultations between Globalstar and GPS satellites occur when the GPS satellites rise above the Globalstar horizon and when the GPS satellites set with respect to the Globalstar. The observation of rising occultations is much more difficult than the observation of setting occultations since the receivers must lock very quickly, as the fastest atmospheric Doppler shift occurs just as the signal becomes visible. For this reason we will focus only on setting occultations. This should not be taken to mean that observations of the rising occultations are impossible - just that it is probably more difficult than the advantage gained from getting twice as many occultations. We already obtain plenty of occultations.

The additional path delay associated with the atmospheric retardation of the GPS signal varies from a few hundred meters in the mid-troposphere to almost a kilometer near the ground in warm, moist regions. In order to measure the atmospheric mass field with enough precision to make 1 m/s wind determinations, temperature determinations to about 0.5 degree Celsius, or moisture determinations to 5%, we will need to measure this additional path delay with an accuracy of 1-2 meters. The occultation geometry is such that an occultation takes approximately 30 seconds to occur from a tangent height of 10 km to the ground and the maximum Doppler frequency of the chirp induced by the atmosphere is about 500 Hz. The path geometry limits our vertical resolution to about 250 meters and, in order to achieve this resolution, we will need to sample the Doppler shift at a rate of about 2 Hz for the 30 second occultation.

The required 1-2 meter accuracy should be within the range of existing Y-code GPS receivers; however, these receivers will have to be modified in order to accommodate the 500 Hz occultation bandwidth. For the option 3 geometry the SNR requirements corresponding to 1 meter path accuracy are approximately 0 dB in the 500 Hz bandwidth on both the cross-link and the occultation link. The simplest on-board processing strategy would be to simply IF limit the signal and sample the occultation video at a 1 kHz sample rate for the 30 second occultation period. For this purpose 8 bit samples would be more than adequate and we would generate 240 Kbits per occultation. Since we would be dealing with approximately 30 setting occultations per orbit this would correspond to a data rate of about 7 Mbits/orbit for each Globalstar satellite. A significantly lower data rate can be achieved if a relatively simple tracking filter is run on the data on the Globalstar satellite, in which case a sampling rate of 4 Hz for the filter parameters corresponds to about 4 Kbits per occultation for a second order filter. This reduced rate in turn corresponds to 120 Kbits/orbit, which should create no problems in the data distribution network.

In either event, the data samples returned would contain all of the available meteorological information to be gained from the occultation so that the process of collecting the occultation data is generally independent of the ultimate products generated from the observations. This means that a system optimized for real-time weather measurements will still produce the high quality data sets needed for long term climate studies.

### D. A Limited Occultation Capability for Water Vapor

In a later section (III) we describe a system for measuring total column moisture through Ka band beacon absorption measurements by <u>ground</u> stations. If we could use the occultation technique between Globalstar satellites operating in the water vapor absorption band as described in option 4, we would have vertical <u>soundings</u> of both temperature and water vapor separately; this is a very large advantage! Option 4 was rejected for two reasons: 1) the steerable antennas required, and 2) the fixed latitude sampling that occurs between satellites in different planes as shown in Figure II.5. Longitudinal coverage is fair to good, but there are gaps in the latitudinal coverage compared to GPS-Globalstar occultations, and there is no polar coverage. Quality global sampling is not possible with satellites in near circular orbits at the same altitude. Coverage of the globe is much better with occultations between GPS and Globalstar satellites.

There is, however, a vital moisture problem just beginning to be researched in the Global Energy and Water Experiment (GEWEX) which virtually requires the type of coverage obtained between pairs of Globalstar satellites. The GEWEX start up time in the late 1990's just matches the launch schedule for the Globalstar satellites. Its main objective is a quantitative understanding of the hydrological budget of the earth. A key question is the latitudinal transport of water vapor from the tropical to polar regions of the earth. This information is crucial to a better understanding of climate. The climate element most important to humankind is the water distribution or changes that might occur in it.

As things stand now there is no satisfactory way to achieve this goal. All means of obtaining water vapor over the oceans using passive microwave sensors measure the <u>total</u> water vapor in the column. Similarly, the method described in section III using Globalstar satellites provides the total water vapor in the column over land. Both are very useful but they do not compare to the utility of the water vapor distribution with altitude. Satellite infrared sounders for water vapor fail in the presence of clouds,

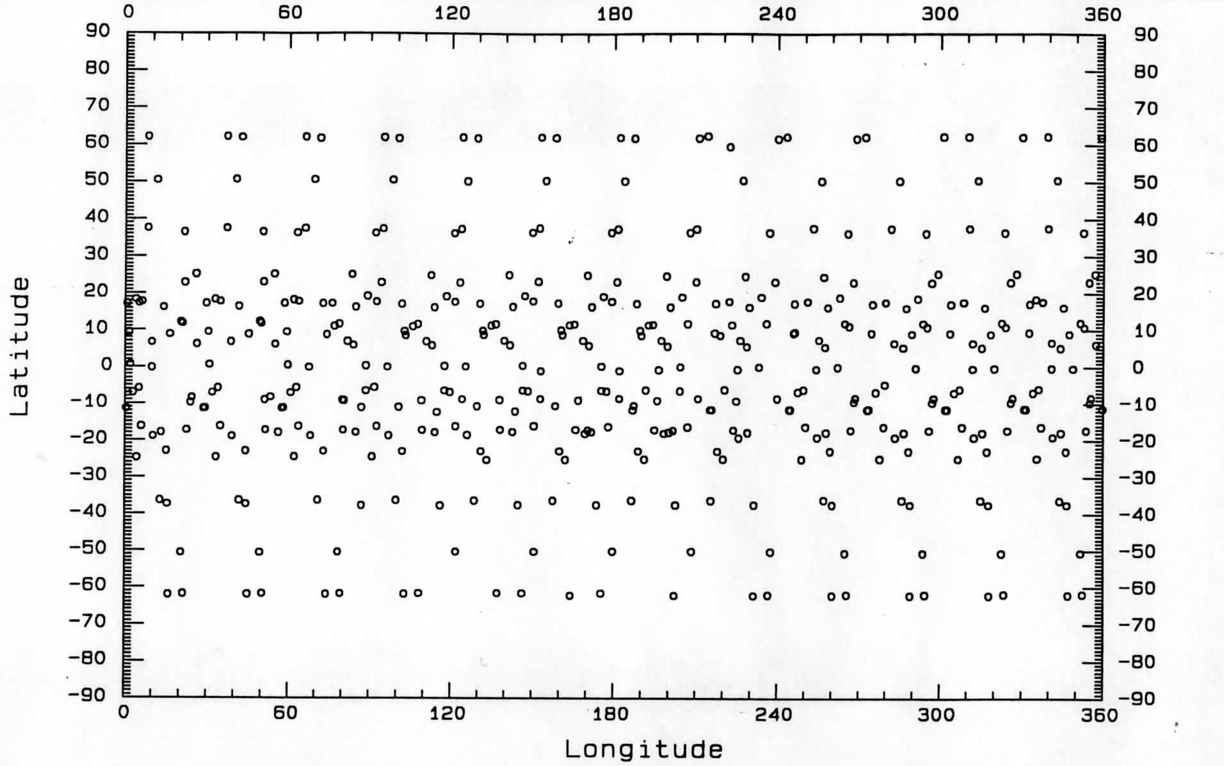

Figure II.5. Locations of entry occultations between a given Globalstar satellite and the other 16 Globalstar satellites that it occults over a one day interval. Each symbol represents an occultation event, with the same symbols occurring at approximately the same antenna pointing angle. Note the absence of polar coverage.

causing a severe "clear bias" in the measurements achieved near the earth's surface when the surface skin background temperature is nearly the same as the near surface atmospheric temperature (a common characteristic of oceanic regimes).

We have already stated that the Globalstar to GPS occultations can yield very high quality winds as a function of height over the globe. We have just mentioned that Globalstar to Globalstar occultations can yield both high quality observations of vertical moisture and temperature along a latitude "fence." Obviously these observations can be used in combination in a model to obtain high accuracy calculations of the water vapor transport through the fence, precisely what GEWEX needs. If the Globalstar satellites are equipped with fixed Ka band antennas, occultations occur at only two latitudes, one on each side of the equator. If only two satellites are so equipped we get two fences, but they are rather open, with roughly 24 "posts" per day around the equator. More satellites equipped with the same fixed angle antenna will give a much tighter fence. Satellites equipped with an antenna pointing at a different fixed angle will give a wider latitudinal fence. A modeling study is needed to accurately determine the number of satellites that need to be so equipped to achieve a given density level of observations.

Undoubtedly there are other possibilities in addition to what we have outlined in this document. SS/Loral would be wise to keep these other options open as they firm up their designs of the Globalstar system.

## E. An Overall System

Figure II.6 portrays a possible data flow architecture, using the geometry of option 3 for illustrative purposes. The data derived from the occultation of the GPS and the reference signal relayed through

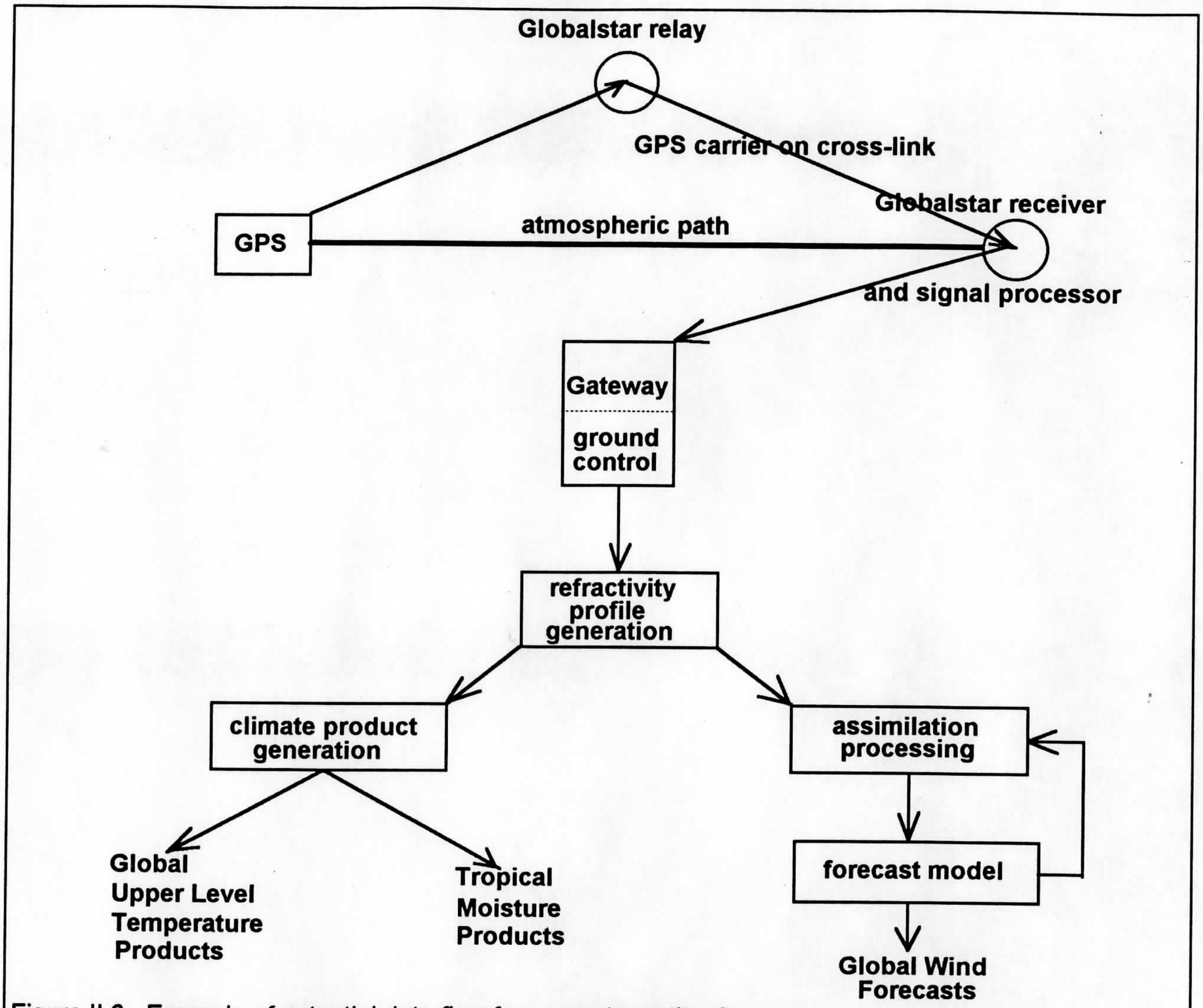

Figure II.6. Example of potential data flow for geometry option 3.

the non-occulted Globalstar undergo initial processing on-board the Globalstar satellite prior to relay to the Gateway (or other ground) station. The data are further processed on the ground to generate refractivity profiles which are then routed into assimilation processing for current weather users, or into climate product generation for modellers and other climate data users.

Thereafter, the data may be assimilated into the current weather arena, such as by generating current wind information for commercial and general aviation, or used to enhance our knowledge of the global climate and further the aims of climate understanding and forecasting.

## III. DETERMINING ATMOSPHERIC MOISTURE THROUGH MICROWAVE (Ka-BAND) ABSORPTION MEASUREMENTS TO GROUND STATIONS

Water vapor is the most important weather producing element of the earth's atmosphere. It is the primary greenhouse gas; the only variable gas that plays a major role in atmospheric dynamics. Radiosondes provide only fleeting point measurements of the water vapor at 12 hour intervals, and at wide geographic spacing. Satellite passive microwave techniques have been able to measure total water vapor over oceans which are mirror-like in that they possess a very low emissivity (i.e., high reflectivity) (Figure III.1). However, these techniques do not work over land surfaces because of their

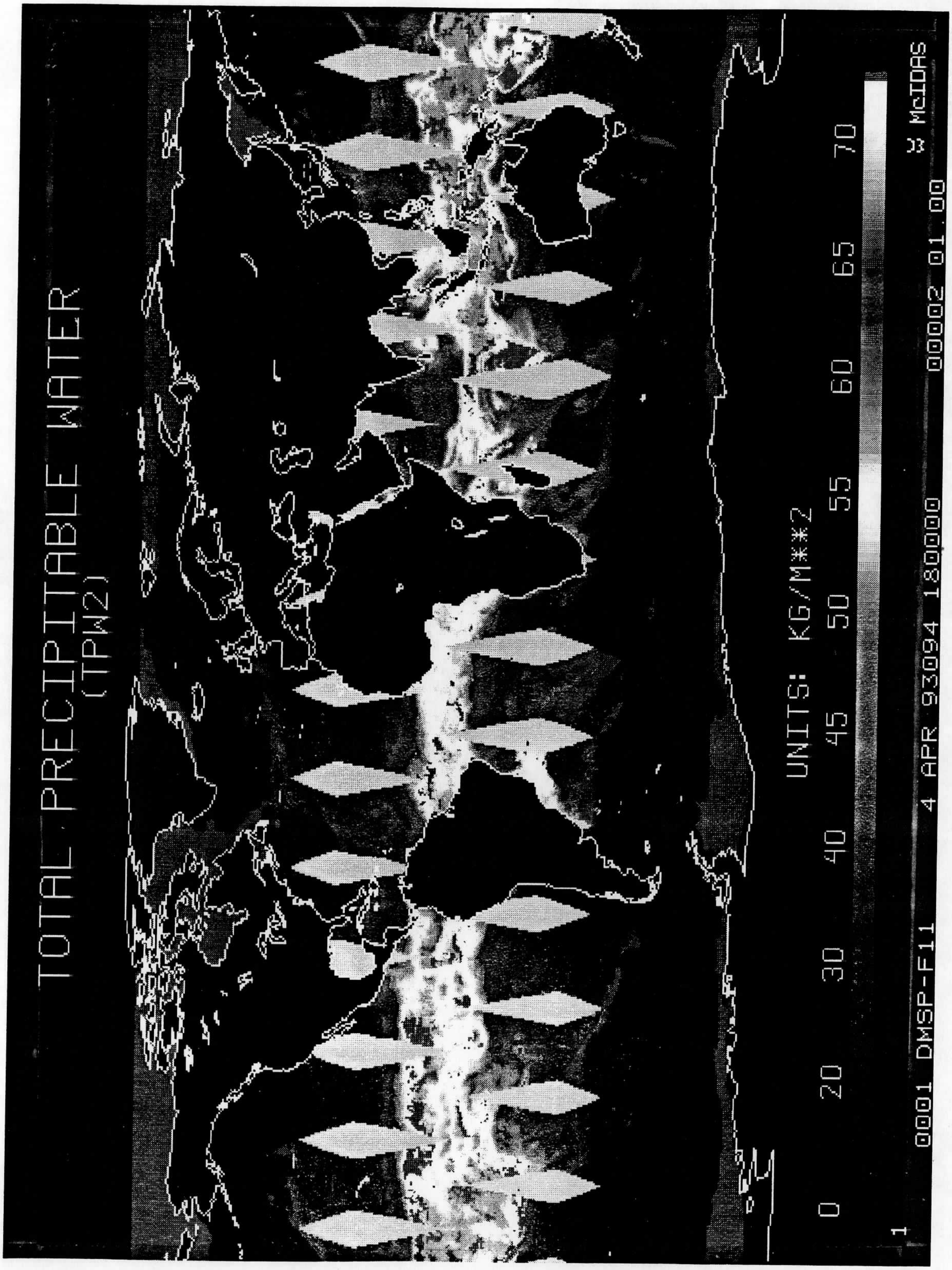


Figure III.1. Spatial coverage of satellite passive microwave determinations of total column water vapor. Land surface microwave background emissivity prevent retrievals over land.

high emissivity background (i.e., over land, there is little contrast between atmospheric water vapor emission and that from the underlying surface).

A direct satellite-to-ground microwave (Ka-band) transmission provides a simple and inexpensive means to measure total column water vapor over land where our current global measurement system is extremely limited. With the Globalstar system this could be done on a nearly continuous basis. A simple addition to the ASOS ground system (Automated Surface Observing System) would provide continuous data collection. The system microwave receivers could be co-located with existing data collection platforms (DCP's) and the potential exists to provide measurements of total liquid water (rainfall) over continents as well.

**A. Theoretical Considerations**

The physical basis for the Ka band satellite to ground observation is illustrated in Figure III.2, which shows the frequency dependence of microwave attenuation for oxygen, water vapor, and two different cloud types. The water vapor attenuation has a well-defined peak, near 22 GHz, that makes it spectrally distinct from the other attenuation sources, which have a relatively slow variation with frequency near 22 GHz. The relative change in atmospheric transmission from the center of the absorption line to the edge of the absorption line is primarily due to water vapor and is essentially independent of the amount of attenuation produced by other contributing sources. This will be shown analytically in what follows.

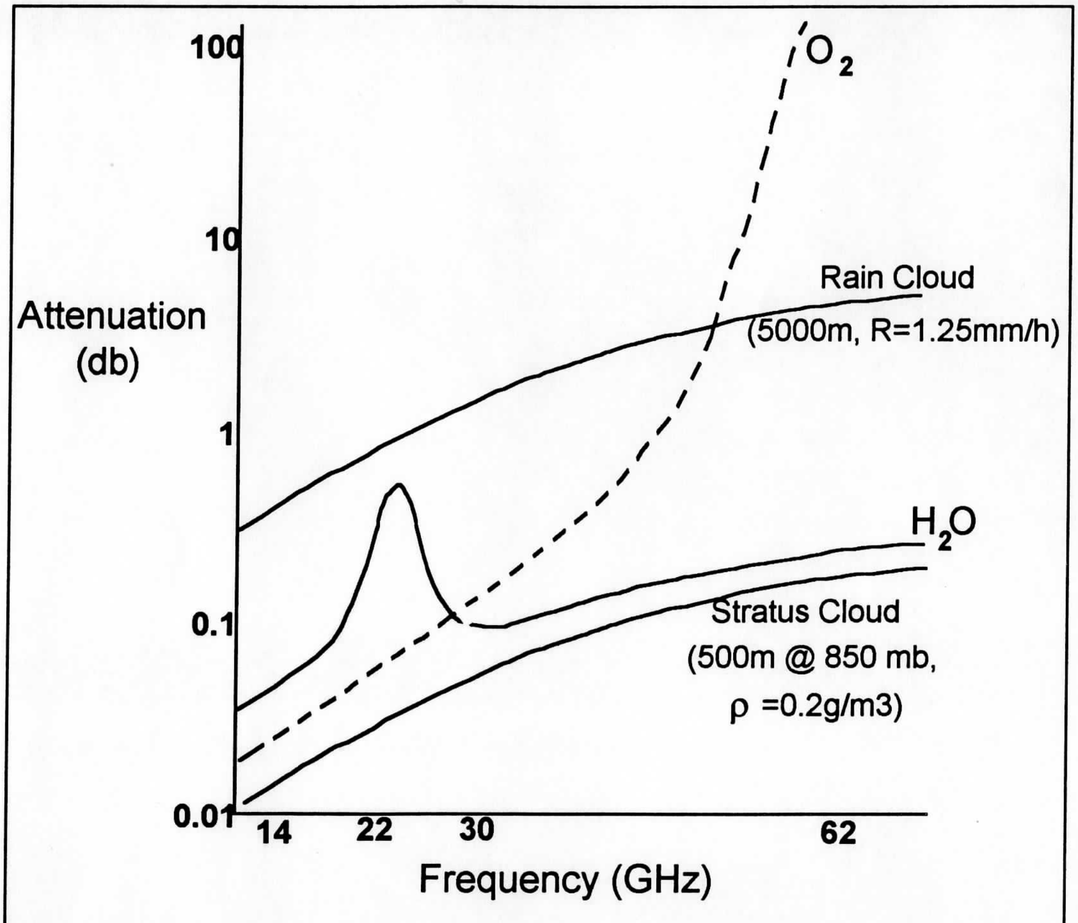


Figure III.2. Microwave attenuation by atmospheric constituents.

The relationship between microwave signal and total column water vapor is fundamentally an equality between the on-line to off-line microwave signal ratio and the column transmission of water vapor. The "column" could be vertical, as it is normally conceived, or it could be horizontal, as is describe in section II for geometry option 4. This can be seen with the help of Figure III.3, which displays the water vapor absorption line in terms of transmission as a function of frequency. The on-line frequency is

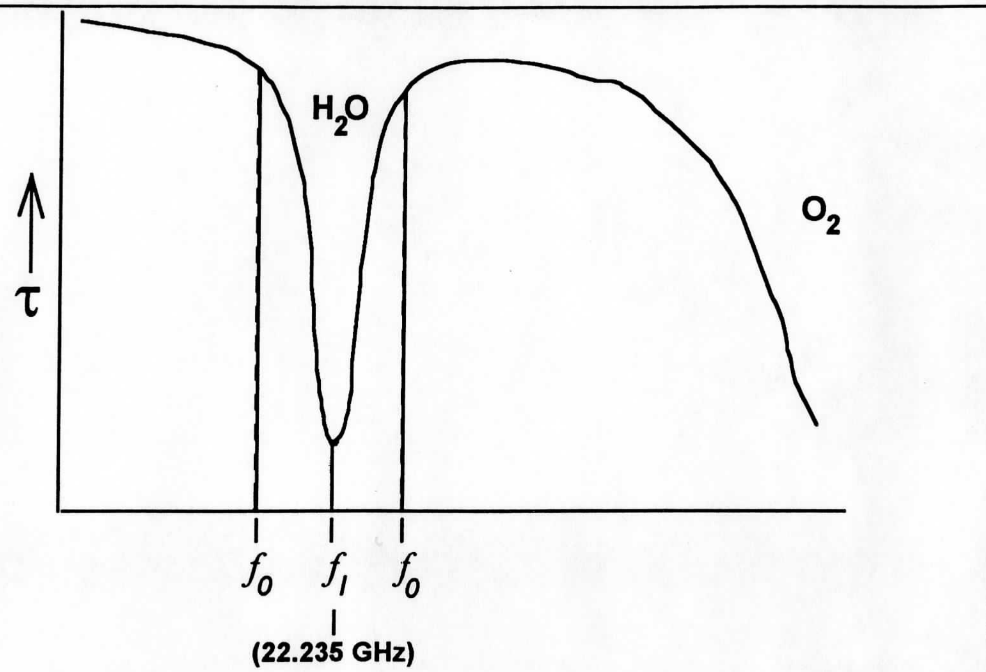


Figure III.3. Transmission variation across the 22 GHz water vapor absorption line.

$f_l$ =22.235 GHz, and the off-line frequency is denoted by $f_o$, shown on either side of the absorption line. (Although we would probably use both sides of the line to establish the transmission of a water-free atmosphere at the central frequency, for the sake of simplicity we will use just one measurement off the line center in the mathematical development.) At a single frequency, *f*, and at angle $(\theta,\phi)$ the receiver signal will be proportional to transmitter power $P_t$, antenna gains $G(\theta,\phi)$, atmospheric transmission due to non-water components $\tau_n$, and transmission due to water vapor $\tau_w$. At two different frequencies $f_o$ and $f_l$ , we can then write

$$
\begin{aligned}
P_r(f_l,\theta,\phi) &= P_t(f_l)G(f_l,\theta,\phi)\tau_n(f_l,\theta,\phi)\tau_w(f_l,\theta,\phi) \\
P_r(f_o,\theta,\phi) &= P_t(f_o)G(f_o,\theta,\phi)\tau_n(f_o,\theta,\phi)\tau_w(f_o,\theta,\phi)
\end{aligned}
\tag{1}
$$

Assuming that non-water transmission is independent of *f* (or has an easily corrected dependence), then the ratio of water transmissions can be written as

$$
\frac{\tau_w(f_l,\theta,\phi)}{\tau_w(f_o,\theta,\phi)} = \frac{P_r(f_l,\theta,\phi)/\,(P_t(f_l)G(f_l,\theta,\phi))}{P_r(f_o,\theta,\phi)/\,(P_t(f_o)G(f_o,\theta,\phi))} = e^{-\frac{1}{g}\int_0^{P_s} kq\,dp} = e^{-S(\theta)} \tag{2}
$$

where the integrated column differential absorption is given by

$$
S(\theta) = -\ln\left[\alpha\,\frac{P_r(f_l,\theta)}{P_r(f_o,\theta)}\right] = \frac{1}{g}\int_0^{P_0} k'\,q\sec\theta\,dp \tag{3}
$$

and where $q$ is the specific humidity and

$$\alpha = \frac{P_t(f_o)G(f_o,\theta,\phi)}{P_t(f_1)G(f_1,\theta,\phi)} \text{ =transmitter/antenna gain constant} \quad (4)$$

$$k' = k_1 - k_0 = \text{ differential water vapor abs. coeff.} \quad (5)$$

Note that absorption by clouds and oxygen do not directly influence the integrated water absorption parameter ($S$), and that absolute knowledge of the transmitter power or antenna gains is not needed; only the product of the ratios at the two frequencies is needed. The solution for the total column $H_2O$ is given by

$$u = \frac{1}{g}\int_0^{P_o} q\,dp = \frac{S(\theta)}{\bar{k}'\sec(\theta)} \quad (6)$$

where $\bar{k}'$ is the vertical mean of the differential water absorption, given by

$$\bar{k}' = \int_0^{P_0} k' q\,dp \Big/ \int_0^{P_0} q\,dp \quad (7)$$

Using a climatological mean value of $\bar{k}'$ yields a relatively small error (< 5%) as shown in Figure III.4, for extreme meteorological situations. Using a forecast profile to determine $\bar{k}'$ will limit this source of error to about 1%. Appendix 3 shows how $\bar{k}'$ variations can be accounted for in the determination of the total column water vapor content. An error analysis was performed to evaluate the performance of the Ka-band absorption measurement technique (Appendix 2). We conclude that for total system errors of 10%, the total column water vapor concentration could be specified with an 8% accuracy, provided that each sample is a product of one hundred time independent measurements.

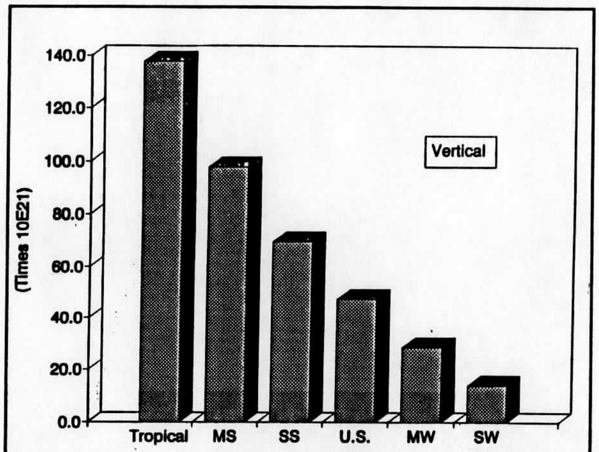


Figure III.4(a). Total $H_2O$ column densities for different types of atmospheric conditions: tropical, Mid latitude Summer (MS), Sub Arctic Summer (SS), US. standard, Mid latitude Winter (MW), and Sub Arctic Winter (SW).

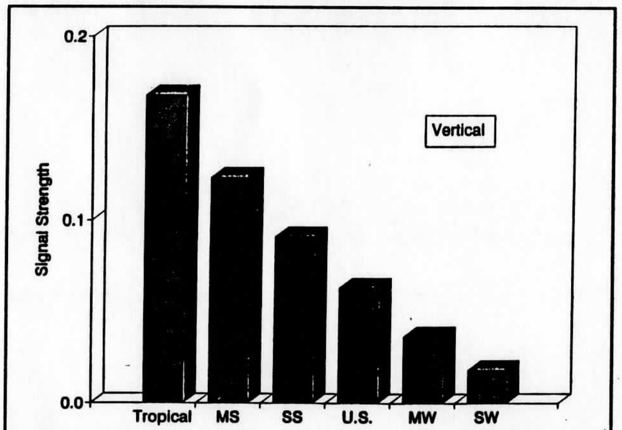


Figure III.4(b) Signal strength for different types of atmospheric conditions: tropical, Mid latitude Summer (MS), Sub Arctic Summer (SS), US. standard, Mid latitude Winter (MW), and Sub Arctic Winter (SW).

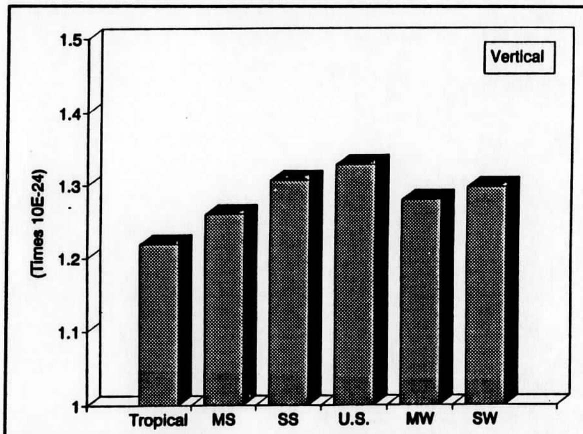


Figure III.4(c) Mean $H_2O$ Absorption Coefficient for different types of atmospheric conditions: tropical, Mid latitude Summer (MS), Sub Arctic Summer (SS), US. standard, Mid latitude Winter (MW), and Sub Arctic Winter (SW).

## B. System Configuration for a Beacon System

### 1. *Baseline Configuration for Beacon System*

The baseline configuration we chose has the Ka-band transmitter on Globalstar satellites and the receiver at ASOS ground stations (Figure III.5). Both the transmitter and receiver use low gain antennas

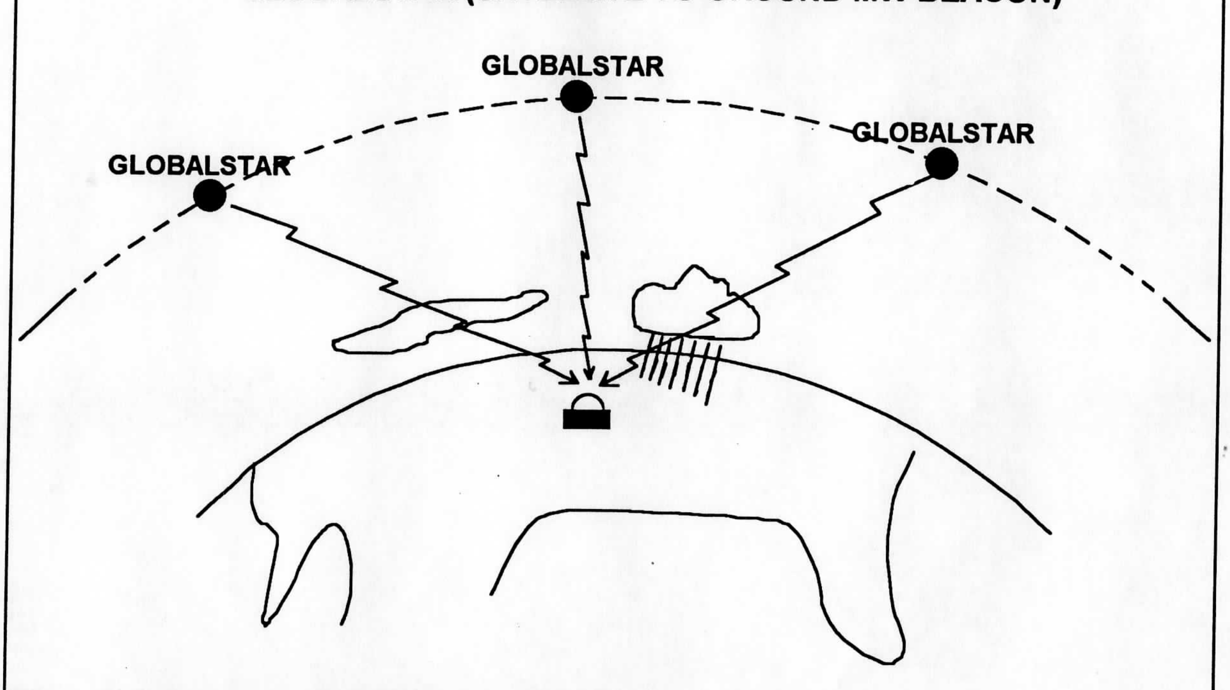


Figure III.5. System configuration for Ka-band beacon.

to avoid problems and costs associated with antenna pointing. Three frequencies (one on-line and one on each side of the line) or swept frequencies (scanning across the absorption line) are possible, depending on frequency allocation.

The virtues of the baseline configuration are as follows: (1) a steerable antenna is not required on either the satellite or the ground; (2) the least expensive hardware (receiver) is on the numerous ground stations; (3) data is locally available on the ground stations; (4) beacons are visible from horizon to horizon, allowing scanning over a wide range of air masses, and facilitating correction of bias effects; and (5) antenna patterns are smooth (they don't look substantially different at different frequencies and different look angles), minimizing introduction of uncertainty in measurement of absorbed power.

The main performance issues of the Ka beacon system for measuring water vapor are (1) the link budget analysis results that are not yet available; and (2) frequency allocation at power levels, frequencies, and duty cycle needed to support the measurement.

### 2. *Ground System and Interface*

Automated Surface Observing System (ASOS) stations can provide the backbone of the ground system. About 1700 ASOS stations will be installed across the US, distributed as shown in Figure III.6. The system configuration features of ASOS stations, as summarized in Figure III.7, allow the user to tailor the sensor complement, external communications, and other capabilities to the local requirements. These features should facilitate the addition of a beacon receiver into the sensor complex. ASOS allows

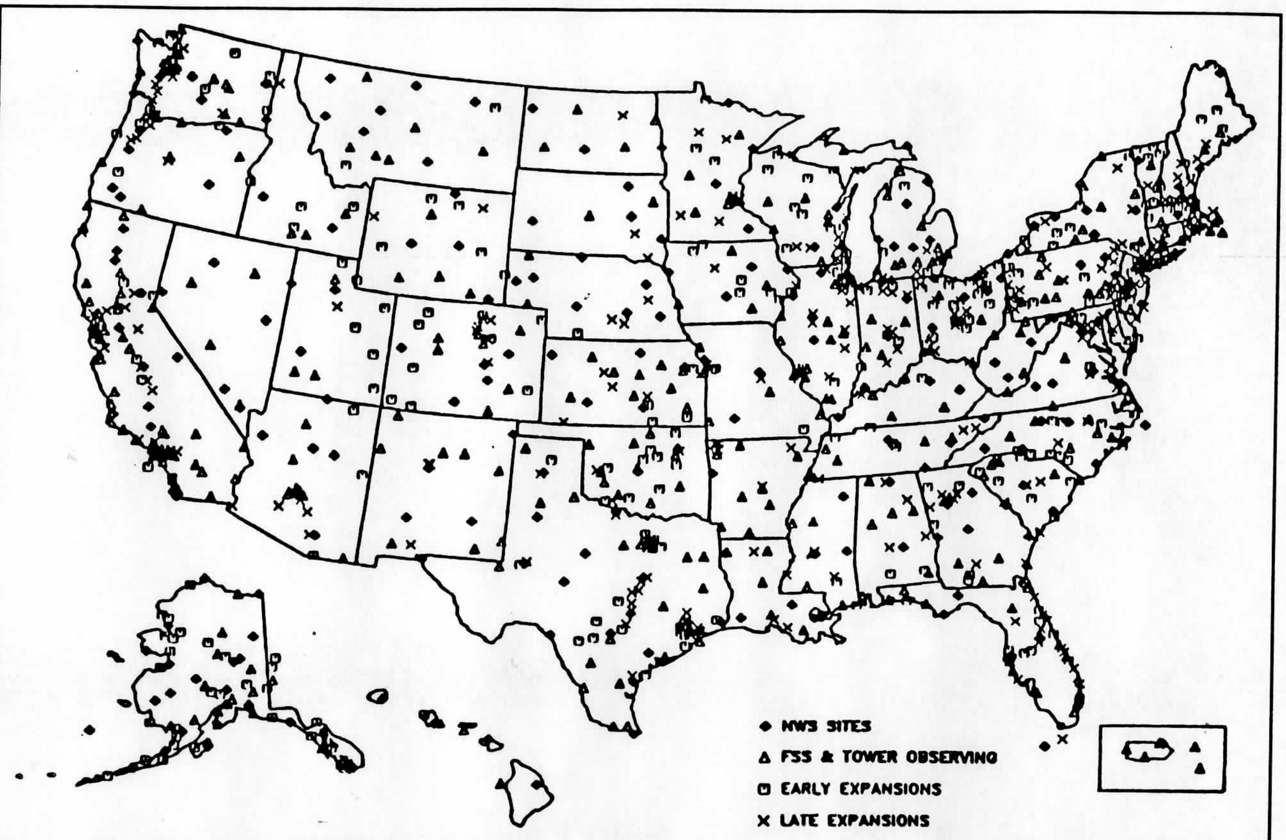


Figure III.6. Projected locations of ASOS stations across the US. (Larry E. Burch, National Weather Service, ASOS Transition and Implementation Branch, W/OSD14, 1325 East-West Highway, Silver Spring, MD 20910)

multiple sensor groups, each group serviced by a data collection package (DCP) that provides sensor power, collects sensor data, and sends data by radio to the Acquisition Control Unit where data is processed and sent to user ports, including the National Weather Service. A Ka-band receiver could be added to ASOS stations as an independent sensor group, or perhaps as part of an existing group. The cost of a DCP (if needed) and associated interface hardware and software remain to be determined.

## IV. MEASURING OZONE CONCENTRATIONS BY RADIO BEACON ABSORPTION

We also investigated the feasibility of measuring the geographical distribution of ozone by the absorption technique described in Section III for water vapor. The technique was not found to be attractive. As documented in this section, the absorption signal is very small, even for an occultation geometry that enhances total ozone amount by about a factor of 40 over near-nadir paths.

The spectral region considered for this application was the 0-60 GHz region where several very weak ozone lines exist. The positions of those lines are illustrated in the transmission spectrum of Figure IV.1, calculated for a path tangent to the earth's surface using the Phillips Laboratory FASCOD3 line-by-line radiative transfer model using the HITRAN 1992 line database. The apparent widths of these lines are very narrow when compared to the widths of the 22 GHz water and the 60 GHz oxygen lines in Figure IV.2, because of the low pressure at the peak of the ozone vertical distribution.

The ozone absorption for paths from Globalstar to the ground (like those considered for water vapor) is quite small, as indicated by the lack of any identifiable ozone absorption features in Figure IV.2. It is apparent that the same approach described in Section III for water vapor is not practical for ozone.

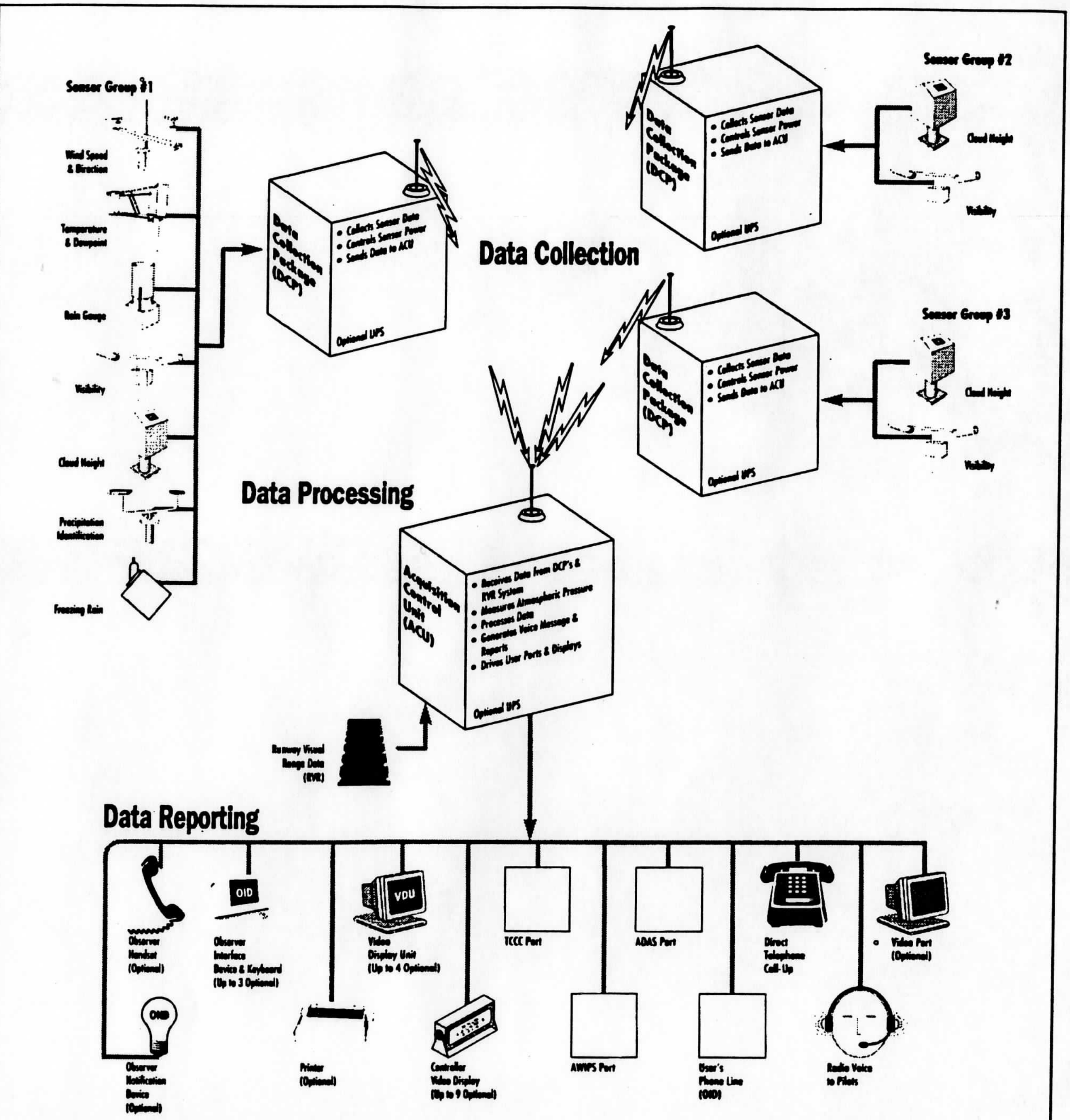


Figure III.7. Functional configuration of ASOS ground stations. (AAI Corporation, Director of Environmental Services, P.O. Box 126, Hunt Valley, MD 21030-0126, Phone 301-628-3890).

The low ozone absorption for the Globalstar-to-ground configuration led us to consider Globalstar-to-Globalstar occultation to increase the path length. The absorption for a 25 km tangent height which emphasizes the altitude region where ozone peaks is illustrated in Figure IV.3. Even with this significant amplification of ozone path length, the maximum absorption for the narrow line at 1.8 $cm^{-1}$ is less than 3%. Also this line overlaps with the prominent 60 GHz oxygen line, making it an impractical choice.

The transmission profile as a function of tangent height for the peak of the absorption line at 37.8 GHz is shown in Figure IV.4. The low maximum signal of 3% absorption combined with the narrowness of the feature would make it very difficult to make accurate measurements of ozone using this approach.

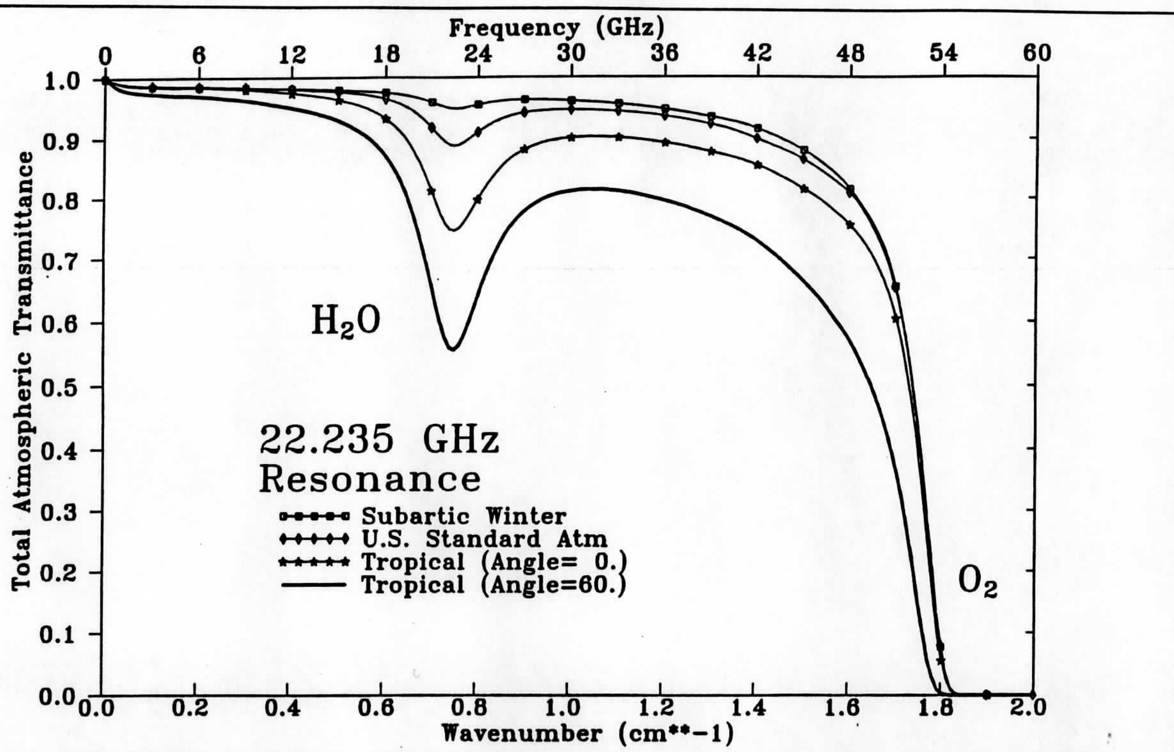


Figure IV.1 Calculated transmission spectra including ozone in addition to water vapor and oxygen, the primary absorbers from 0 to 60 GHz. Note that for zenith angles from 0 to 60 degrees, the ozone lines are essentially unidentifiable.

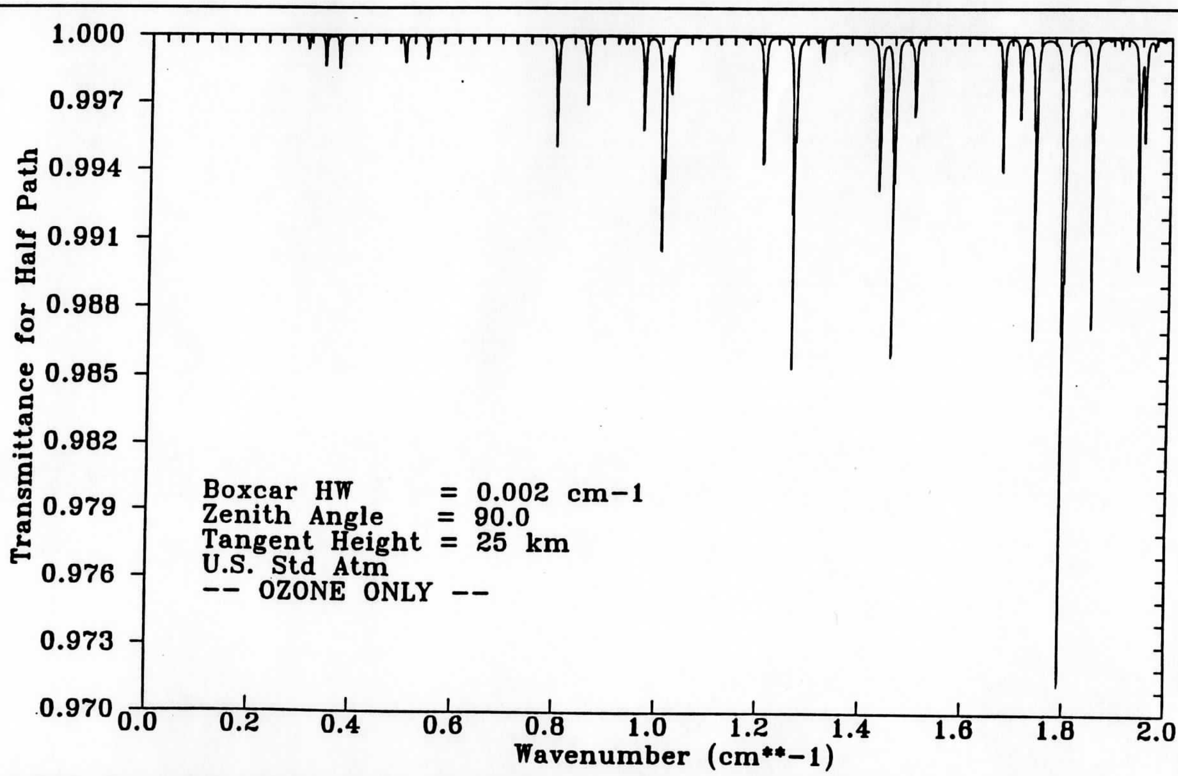


Figure IV.2 Ozone transmission from a line-by-line calculation for the U.S. Standard Atmosphere with a tangent height of 0 km.

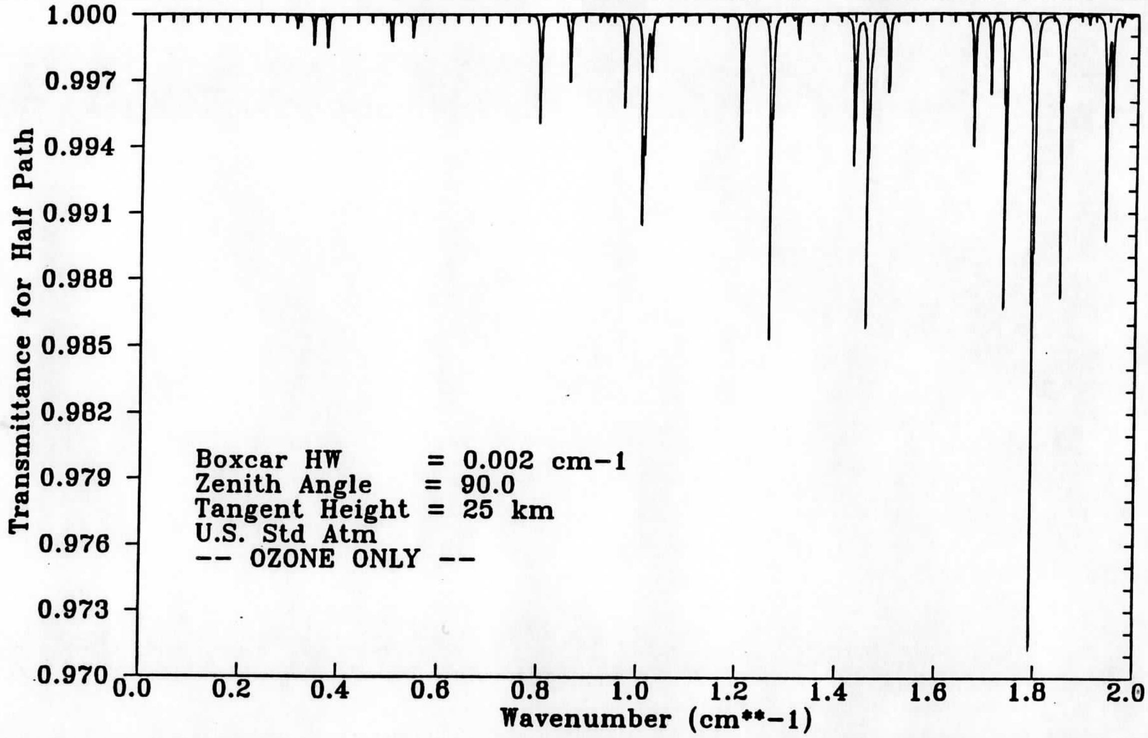


Figure IV.3 Ozone transmission from a line-by-line calculation for the U.S. Standard Atmosphere with a tangent height of 25 km.

Given the relative difficulty of the measurement, especially considering the more difficult implementation for the occultation configuration, we did not feel that this option deserved further attention.

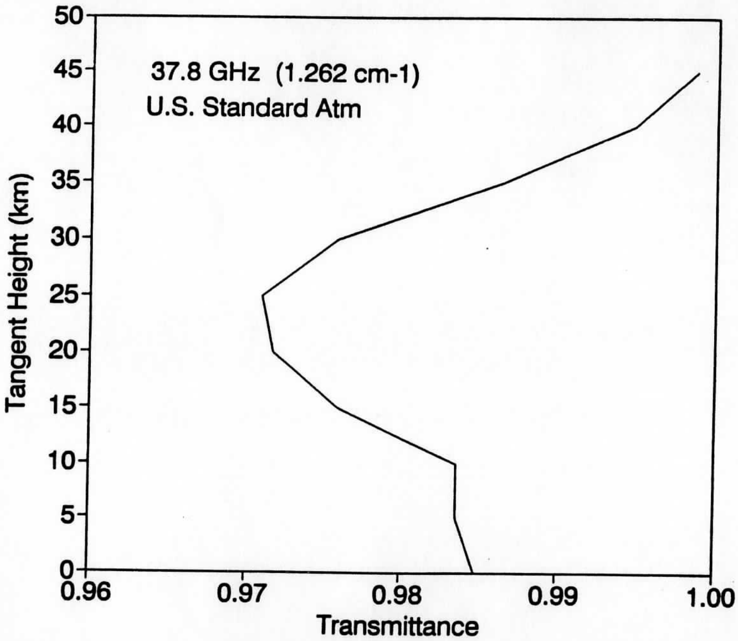


Figure IV.4 Ozone transmission profile as a function of tangent height for the U.S. Standard Atmosphere.

## V. OBSERVATIONS, PRODUCTS AND MARKETS

In this section we will review the quantities which can be directly observed with the Globalstar system, discuss the "products" which can be generated from the observed quantities, and attempt to identify potential markets for these products.

In the preceding sections we discussed methods for observing five variables:

1 Atmospheric refractive index from Globalstar-GPS occultations. These measurements represent a combination of atmospheric density and humidity effects. They have good vertical resolution (approximately 500m) but modest horizontal

resolution (200 km along occultation track). The measurements have good, near global distributions.

2 Limited atmospheric moisture data using Globalstar-Globalstar occultations in the 22 GHz band. The measurement characteristics are similar to product 1; however, due to the synchronous Globalstar satellite orbit geometries, the occultation ground tracks are located in "fences" at two latitudes per instrumented satellite pair.

3 Atmospheric integrated column moisture measurements derived from attenuation measurements along a Globalstar to ground station path. These measurements have good temporal frequency and good horizontal resolution (1-3 Km ). The horizontal spacing is determined by the distribution of receiving stations and is presumably most of the continental US.

The next step in our analysis is the determination of how these observations can be used to generate meteorologically significant information that can form the basis for marketable products. The data products labeled 2 and 3 above are basically meteorological products already. However, the occultation soundings (product 1) deserves some attention since the radio refractivity is not a commonly used atmospheric state variable. In particular, we can expect to generate:

1.1. Estimates of atmospheric density using forecast model values for the moisture fields to make corrections for the effects of water vapor. The density values are directly useful since they can be easily converted into geopotential height and used to calculate winds using well known dynamical techniques. However, in warm moist regions where the water effects dominate the refractivity, the accuracy of this approach is not high. This product is probably best used to generate measurements of global wind fields for altitudes above 2-3 km at high latitudes and 4-5 km in tropical latitudes. The altitude limitations by water vapor do not hinder the use of the wind data for commercial aviation whose flight cruise altitudes are usually well above 5 km.

1.2. Estimates of atmospheric humidity through the complement of the 1.1 procedure. These values can only be expected to be useful in relatively warm, moist regions such as tropical atmospheres below 2-3 km and the lowest 1-2 km of the mid-latitude atmosphere.

1.3. The direct use of refractivity data into operational forecast models. This is probably the best use of the occultation data since the forecast model assimilation process is the optimal way of making the separations described in 1.1 and 1.2. The difficulty here is simply that operation forecast modeling groups tend to be very conservative and the ability to market this product is far from assured. In many ways this approach parallels the direct assimilation of IR sounder radiance data into the model which has been proposed for more than five years and is just now becoming a reality at operational modeling centers.

All of the products described above (1.1, 1.2, 1.3, 2, and 3) would represent significant new observations of atmospheric variables and thus potentially valuable products. The difficulty lies in that fact that the natural customers for much of the data are governmental agencies such as NOAA and NASA and there are no good examples to date of these agencies making commitments to buy data from a privately funded observing system. The most attractive products for government purchase appear to be:

- Occultation products (1.1, 1.2 or 1.3) for use in operational weather forecasting models. This data will fill important data voids and would have a real impact on medium range weather forecasts. The value of this market is hard to assess however since the products are best suited to global medium range applications and the current NWS direction appears to be focusing on improving shorter range regional scale products which will be affected less by products of this sort. However, the European Centre for Medium-Range Weather Forecasts (ECMWF) in Shinfield Park, Reading, U. K., is a possible market for this data.

- Column water vapor products (2) to augment the new mesoscale observing systems such as the wind profiler networks. This product is well positioned for the current NWS interests and the major questions seem to be the costs of the ground system and comparisons in terms of cost with less capable upward looking microwave and IR radiometers which can make similar, but lower quality observations.

- All of the products listed above, but 1.1, 1.2 and 3 in particular, are of critical importance to new international climate initiatives such as GWEX, the World Meteorological Organization's Global Water and Energy Experiment. The total cost of the global efforts is expected to be several hundred million dollars; however, the mechanism for selling these products is unclear. The Globalstar-Globalstar moisture "fence" measurement (2) can play an especially critical role in achieving the characterization of global water fluxes, a major GWEX goal which otherwise may not be achievable.

In addition to the governmental customers, we have identified one significant potential commercial market, the use of global occultation wind data (1.1) to provide high quality short range (1-24 hour) forecasts of winds for aviation purposes. This has the significant advantage of being a self contained value-added product. Using this system in conjunction with a straightforward model assimilation scheme (see Figure II.6.) should provide a very high quality global wind product with accuracies on the order of 1 m/s and horizontal resolutions of 50-100 km. We would expect the most promising markets for these product to be in two basic areas: wind forecasts for commercial aviation in regions where current forecasts are currently fairly poor, such as the Pacific Ocean and the Southern Hemisphere. Current wind forecasts over Northern Hemisphere land masses and the Atlantic Ocean are fairly good and a new wind product is probably of less value in these regions. In addition to the commercial market, a nowcast and forecast wind product for civil aviation and business jet users might be quite successful, particularly if distributed over cellular phone links. These users typically do not have nearly as good an access to high quality forecast products and might represent a significant market if the distribution system was effective and convenient.

## VI. CONCLUSIONS

1. Atmospheric density (and therefore atmospheric winds) by occultation measurements appears very promising. The outstanding features of the technique are:

*a. All weather, virtually continuous coverage over the globe.* The GPS to Globalstar occultations cover the earth to within two degrees from each pole. With additional information about the near surface water vapor distribution, thousands of soundings through clouds, aerosols and rain are possible each day from altitudes of about 60 km to near the surface over oceans and land surfaces. The high vertical resolution of 0.5 to 1.5 km is a major advantage over presently used nadir viewing IR or microwave sounding systems.

*b. The carrier phase observations are very precise.* This is because they are based on first principles and will be operating under high signal-to-noise conditions. On the other hand, current IR and microwave sounding systems measure differences in amplitude observations which are much less precise in the low signal-to-noise environments characteristic of this type of observation. We can count on a factor of 3 - 5 improvement over presently used systems whose accuracy even under ideal cloudfree conditions is no better than 1.0 degree Celsius when expressed as temperature. Typically that error is more like 1.5 - 2.0 degrees.

*c. The incredible observational stability.* Strange as it may seem, occultation observations do not require any "instrument" which requires calibration and which can change with time. All observations use the stability of the atomic clock of the GPS system. All Globalstar GPS receivers, each slightly different, will behave the same. Observations made today have the same calibration as those which will be made 50 years from now. One can thus make meaningful tests of possible global warming, today's key global change concern.

2. Atmospheric water vapor measurements by absorption in the microwave portion of the spectrum are quite feasible using either of two methods, assuming that there are no frequency allocation problems. Each of these methods uses the change in amplitude ratio of the received signals that straddle the 22.4 GHz water vapor band to give an independent observation of the water vapor content of the atmosphere. One method gives the total water vapor in the atmospheric column. It has the advantage of high

horizontal resolution over land, a parameter required for improved severe weather prediction. The second method uses occultations between sister Globalstar satellites. It has the advantage of good vertical resolution but does not have sufficient global coverage to allow us to eliminate the GPS to Globalstar occultation coverage.

(There is also a possible third approach. Instead of using the amplitude ratio as the observable, one might instead use the delay difference between the signals which straddle the band and obtain much higher accuracy independent of antenna pattern information which might affect the amplitude ratio. Due to signal dispersion, the index of refraction will be different on each side of the 22.4 GHz water vapor line. Delays are also much easier to measure than amplitudes. See the next section).

3. The simultaneous observation of atmospheric density and atmospheric water vapor is very powerful system attribute indeed, and should make the data very marketable to governments the world over as well as to value added users in the private sector. The atmosphere's index of refraction can be divided into a "dry" term and a "wet" term. As long as the atmosphere is cold (middle troposphere and above or winter latitudes) the wet term can be ignored or estimated by a variety of methods. Not so for the warmer lower latitudes or altitudes. Having independent simultaneous information on the global water vapor distribution to use to refine the density observations in moist conditions is the "ultimate" system and should set a new standard for the quality of such observations for the global weather observing system.

4. Ozone determination using absorption techniques for a Globalstar beacon are not practical.

5. Add a Store and Forward capability to Globalstar satellites. During discussions of an early draft of this report, SSI was informed that SS/LORAL was considering adding a store and forward capability to the Globalstar spacecraft. In Section II.C (pages 3 and 4) we show that the expected data volume is only 120 Kbits/orbit. This should be no problem over continents where a gateway station is available to receive the transmitted data. On the other hand, over large reaches of the ocean such as the Pacific or Indian Oceans, a sufficient number of gateway stations may not be available to always have one within line-of-sight. While the delays induced by on board data storage would be completely unacceptable for telephonic communications, the same is not true for most meteorological or oceanographic observations. For example, a radiosonde observation which may require up to two hours to complete is assumed to occur at flight launch time. Similarly, GOES takes about twenty minutes to complete a full disk image, but it too is regarded as if it were an observation taken at the start of image scan time. The implications for global coverage of adding a data store and forward capability to Globalstar are enormous, and apply to oceanic as well as land surface observations. This clearly warrants further study, which SSI is able to do.

## VII. SOME CONCLUDING THOUGHTS

There is no question that a dual Globalstar system which would provide global high vertical resolution temperature and moisture data is a great leap forward in meteorological data acquisition, now the limit of the science of weather prediction. It is generally agreed that numerical model performance is limited by inadequate data, especially over the oceans. The question is, "How do you sell this to governments?"

What we are concerned with is how the new technology represented by the Globalstar system can be woven together to solve an important problem not presently solved. First, we must realize that it is really not new technology; it is an old technology that has been used in exploring the solar system for many years. The opportunity to use it on the earth is obvious but is a new application.

A look at past technologies in the marketplace shows common factors. In the weather marketplace, an earlier technology is already present which provides a vital function, and reaps substantial monetary support from the general public as well as special "publics" through added value. Even though the new technology might do a better job at lower cost, the difference in performance between the old and the new technology must be substantial. When the improvement is small, the old way can maintain the

status quo. When the improvement is substantial, the old technology is swept away. Its funds are subsumed by the new technology. In addition, the newer technology often substantially enlarges the market. People are willing to pay more total money for a less expensive product that does more.
In meteorological and oceanic satellite planning up to the present, the notion has always been to minimize the number of satellites required for a given objective. As a result, these satellites have grown larger and larger and more and more costly. The notion of having dozens of smaller satellites has not been politically feasible for the geophysical satellite planning community. Undoubtedly, there are other possibilities in addition to what we have outlined in this document; one of these with a large potential market is oceanography.

A recent paper in *OCEANOGRAPHY* (Sharp and McClain) complains almost bitterly in "Comments on the Ocean Observing Capabilities, Indicator Species as Climate Proxies, and the Need for Timely Ocean Monitoring" about the sorry state of affairs in ocean monitoring. In many instances, the needed data is already being collected, but it isn't being communicated to the potential users. It does not take much imagination to visualize the large potential market that the Globalstar system can open. These are not only from commercial and research ships, but moored and drifting buoys also. In the future, there will be hundreds of these buoys on the world's oceans. The present ARGOS system is already saturated.

How can one assess the value of these new opportunities? Definitive model tests (Observing System Simulation Experiments, or OSSE's) are the traditionally way to evaluate the performance of proposed observing systems. They are particularly valuable for evaluating composite observing systems such as the atmospheric density/water vapor system previously proposed that uses both GPS to Globalstar and Globalstar to Globalstar occultations. One not only obtains good information on the overall performance of the system, but can also study the performance of more restricted systems. OSSE information is particularly valuable when attempting to sell to the government, as this is the test which they have been using to verify the performance of present systems. The Space Science and Engineering Center (SSEC) at the University of Wisconsin-Madison is well equipped to do these tests. They have the models and the computing capability essential to the task, including a massively parallel computer. It is important to conduct such tests before SS/Loral makes a strategic or major financial commitment to an atmospheric density/water vapor system on the Globalstar fleet. While these OSSI's can readily be performed at SSEC independent of SSI, SSI is willing to facilitate or assist in any manner that SS/Loral would find helpful.

We now know enough to say that differential time delay observations across the 22.4 GHz water vapor band will provide independent water vapor observations. The trouble is we don't know quantitatively how well it will work without further study. The differential time delay technique should be much easier to implement than the amplitude ratio approach proposed in section III, and because of that warrants further study. In particular, the effects of other ground and space based 22.4 GHz noise sources need to be considered. It is conceivable that random pseudo noise bursts can be considered as the signal source and can serve as a means to reduce or eliminate interference.

Finally, we cannot resist the mention of two big IF's. If the extra delay in the wet term due to the dispersion in the 22.4 GHz water vapor line as mentioned in the conclusions turns out to be large enough (several meters) and IF the DOD can be convinced to add a suitable 22.4 GHz transmitter to only six GPS satellites, modulated with the same signals as the two transmitted carriers they now have, it becomes possible to have a system with six times the coverage as shown on the cover page. This system would measure both the index of refraction for the "dry" term and a separate one for the "wet" term, yielding a superb system for the future (maybe sooner since all GPS satellites are not on orbit yet and of those already on orbit, some may have to be replaced). Globalstar satellites would require a 22.4 GHz received be added. The same signal processing system as presently proposed would serve. Further, no 22.4 GHz transmitters would be required on Globalstar satellites! The system would be cheaper and better. The additional water vapor information could also serve the DOD purposes.

SS/Loral would be wise to keep these other options open as they firm up their designs of the Globalstar system. The ocean requires in situ observations. The space component of this initiative comes in the collection of this all important data via a Globalstar system. In our view, the advantages of the GPS-Globalstar system are so great that we have reached a point where the old way will certainly be swept away by the new.

## Appendix 1
## GPS-Globalstar Occultation Information

To assess the usefulness of the atmospheric occultation profiles, knowledge of the spatial and temporal distribution of the occultations and the global coverage obtained in a single day is required. Key questions regarding such coverage include:

- How dense is the sampling?
- How uniform is it globally and diurnally?
- Are there any special aspects regarding the occultation geometry for a given pair of satellite constellations?

Some general observations on the nature of the orbits of the GPS and Globalstar constellations.

- Both have similar inclinations, 55° and 52° respectively.
- Periods differ by a factor of 6. The Globalstar satellites have a period of about 114 minutes (1,391 km altitude) whereas the GPS satellites have a period of 12 hours and are in a much higher orbit (20,000 km altitude).

Globalstar-GPS occultation specifics:

- Any Globalstar satellite will generally occult a given GPS satellite twice per orbit - one entry occultation and one exit occultation.
- Over a 24-hour period, a single GPS satellite and a single Globalstar satellite can be expected to have as many as 24 occultations.
- The total number of occultations for 48 Globalstar satellites and 18 GPS satellites is thus approximately 48*18*24 = 20,736 occultations per day. This number is approximate because the satellites are in different planes and the relative motion has been ignored in this calculation.
- GPS-Globalstar occultations are one-way occultations in which the GPS signal is monitored on the Globalstar.
- When a Globalstar is receding from a GPS satellite and enters the geometric shadow zone of the earth, it actually keeps on receiving the GPS signal for a short while due to the bending of the radio beam. This is the "Entry" or ingress occultation. The typical bending due to the intervening atmosphere is generally less than about 3°. Due to the atmospheric bending of the GPS signal, the just-occulted GPS satellite is visible to that Globalstar satellite a short time later, prior to emerging from the geometrical shadow zone projected by the earth. This is the "Exit" or "Egress" occultation.

Similarly, the 48 Globalstar satellites also produce Globalstar-Globalstar occultations, but only between specific pairs of satellites.

- As there are 8 planes of 6 evenly spaced satellites, the satellites in a given plane will never occult each other (circular orbits) and in fact, for a given satellite, its immediate leading and trailing same plane neighbors are always in view. Indeed, no occultations will even occur between satellites in adjacent planes.
- Only certain satellites in the other five planes occult a given Globalstar satellite. A total of 16 pairs can be found for each Globalstar satellite that occult each other twice per orbit, producing no more than 25 entry or exit occultations per pair per day. Some pairs occult much less often.

- The occultations between a given pair of Globalstar satellites are restricted in latitude coverage. Basically a pair produces occultations only at two latitudes, one in each hemisphere, and these latitudes are distributed more or less evenly in longitude or time.

Our methodology for examining occultation frequency and geographic location included:

- A Globalstar constellation of 48 satellites in 8 planes of 6 equally spaced satellites with a phase angle of 7.5° between the adjacent satellites in a WALKER 8/8/1 pattern was assumed. Satellite orbital elements were synthesized into standard two line element format and are shown in Table A1-1.
- The 18 currently active GPS Block II satellites were assumed. Their orbital elements are shown in Table A1-2.
- Ephemeris calculations were run every 30 seconds for a period of 24 hours for this configuration.
- Only the GPS-Globalstar occultation study results are presented here. Initial results of the distribution of mutually occulting Globalstar satellites were presented at the first SSI SS/Loral meeting in Madison in February 1993. Based on the discussion of the different occultation geometries possible, the directive given to SSI was to concentrate on the GPS-Globalstar occultations
- Along with the x,y,z position of each satellite, the corresponding velocity components were also computed allowing the computation of Line-Of-Sight relative velocity between any two occulting satellites.

Simplifying assumptions made were:

- A spherical earth with a radius of 6,356 km (polar radius). This assumption allowed the latitude of the occultation location (i.e. the location where the radio beam is tangent to the earth) to be computed directly.
- The maximum bending of the radio waves by the atmosphere (neutral and ionosphere) is 3°.

Conclusions:

- Globalstar-Globalstar occultations occur between ± 75°.
- GPS-Globalstar occultations occur at latitudes as high as ±88°.
- The occultations are very uniformly distributed in the hour-of-day and longitude. The latitude sampling is somewhat uneven with the region around ± 20° being sampled most, and the polar regions the least.
- Approximately 1,000 occultation events (both entry and exit) occur every hour, or one roughly every 3 to 4 seconds. Figure A1.1 shows the distribution of entry occultations as a function of latitude (*all* longitudes) for one Globalstar to all GPS satellites. This should not be confused with the cover picture, which is one GPS satellite versus all Globalstar satellites.
- Both the Entry and Exit occultations last typically no more than 90 seconds during which the occulting radio beam samples the atmosphere and the ionosphere of the earth to altitudes of 300 km. The tropospheric altitudes are sampled in a time as short as about 10 seconds. The typical "horizontal" path length of the radio beam through the ionosphere/atmosphere is generally about 200 km, with the entry and exit locations separated typically by about 2° in latitude and longitude.
- The relative velocity along the Line-of-Sight (LOS) between the two occulting satellites is typically no more than about ±6 km/s for the GPS-Globalstar occultations (positive, for Entry occultation when a Globalstar satellite is receding from a GPS satellite; negative for Exit occultations when the Globalstar satellite is approaching the GPS satellite), and is relatively constant for a given occultation. The corresponding

contribution to the frequency variation is thus small and changes very slowly over the occultation duration. This is important to the precision with which the bending due to the atmosphere can be recovered to invert the atmospheric temperature profile.

- The GPS and Globalstar constellations also produce a peculiar class of occultations that last somewhat longer than 90 seconds--as much as 6 to 8 minutes. These are grazing occultations in which a Globalstar satellite moves along the apparent horizon of the earth as viewed from the occulted GPS satellite. These grazing occultations are also characterized by very small LOS relative velocity magnitudes (typically < 0.5 km/s) between the occulting satellites. Typically the entry and exit events follow without any delay as in the case of the other occultations. Due to the extended duration of such events, the path between the beginning of the occultation and the transit through the atmosphere is much longer than for the other type of occultations and may approach several hundred km. The exact duration and occurrences of such occultations will depend critically on the actual orbits achieved for the Globalstar satellites and their stability. As the length of the occultation path is substantially longer than the normal occultations, usefulness of such occultations is suspect.

Figures A1-1 to A1-3 show the occultation positions, distance and doppler velocities for occultations between a single Globalstar satellite and the GPS constellation. Additional Globalstar satellites will increase the coverage density with similar space-time structure.

**Table A1-1**

Simulated orbital elements for Globalstar satellites (Walker constellation, 8 planes, 6 satellites per plane, 7.5° phasing).

```
GLOB0101
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000   0.0000 0010000  0.0000   0.0000 12.62190680   05
GLOB0102
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000   0.0000 0010000  0.0000  60.0000 12.62190680   12
GLOB0103
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000   0.0000 0010000  0.0000 120.0000 12.62190680   20
GLOB0104
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000   0.0000 0010000  0.0000 180.0000 12.62190680   37
GLOB0105
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000   0.0000 0010000  0.0000 240.0000 12.62190680   45
GLOB0106
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000   0.0000 0010000  0.0000 300.0000 12.62190680
53GLOB0201
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000  45.0000 0010000  0.0000   7.5000 12.62190680   62
GLOB0202
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000  45.0000 0010000  0.0000  67.5000 12.62190680   79
GLOB0203
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000  45.0000 0010000  0.0000 127.5000 12.62190680   87
GLOB0204
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000  45.0000 0010000  0.0000 187.5000 12.62190680   94
GLOB0205
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000  45.0000 0010000  0.0000 247.5000 12.62190680  103
GLOB0206
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000  45.0000 0010000  0.0000 307.5000 12.62190680  111
GLOB0301
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000  90.0000 0010000  0.0000  15.0000 12.62190680  123
GLOB0302
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000  90.0000 0010000  0.0000  75.0000 12.62190680  130
GLOB0303
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000  90.0000 0010000  0.0000 135.0000 12.62190680  148
GLOB0304
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000  90.0000 0010000  0.0000 195.0000 12.62190680  155
GLOB0305
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000  90.0000 0010000  0.0000 255.0000 12.62190680  163
GLOB0306
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000  90.0000 0010000  0.0000 315.0000 12.62190680  171
GLOB0401
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000 135.0000 0010000  0.0000  22.5000 12.62190680  182
GLOB0402
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000 135.0000 0010000  0.0000  82.5000 12.62190680  199
GLOB0403
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000 135.0000 0010000  0.0000 142.5000 12.62190680  208
GLOB0404
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000 135.0000 0010000  0.0000 202.5000 12.62190680  216
GLOB0405
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000 135.0000 0010000  0.0000 262.5000 12.62190680  223
GLOB0406
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000 135.0000 0010000  0.0000 322.5000 12.62190680  231
GLOB0501
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000 180.0000 0010000  0.0000  30.0000 12.62190680  243
GLOB0502
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000 180.0000 0010000  0.0000  90.0000 12.62190680  250
GLOB0503
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000 180.0000 0010000  0.0000 150.0000 12.62190680  268
GLOB0504
1 00000R       93 51.00000000 .00000000 00000-0 00000-0 0    1
2 00000  52.0000 180.0000 0010000  0.0000 210.0000 12.62190680  276
```

**GLOB0505**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 180.0000 0010000 0.0000 270.0000 12.62190680 283
**GLOB0506**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 180.0000 0010000 0.0000 330.0000 12.62190680 291
**GLOB0601**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 225.0000 0010000 0.0000 37.5000 12.62190680 302
**GLOB0602**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 225.0000 0010000 0.0000 97.5000 12.62190680 319
**GLOB0603**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 225.0000 0010000 0.0000 157.5000 12.62190680 327
**GLOB0604**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 225.0000 0010000 0.0000 277.5000 12.62190680 342
**GLOB0605**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 225.0000 0010000 0.0000 277.5000 12.62190680 342
**GLOB0606**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 225.0000 0010000 0.0000 337.5000 12.62190680 350
**GLOB0701**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 270.0000 0010000 0.0000 45.0000 12.62190680 362
**GLOB0702**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 270.0000 0010000 0.0000 105.0000 12.62190680 370
**GLOB0703**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 270.0000 0010000 0.0000 165.0000 12.62190680 387
**GLOB0704**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 270.0000 0010000 0.0000 225.0000 12.62190680 395
**GLOB0705**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 270.0000 0010000 0.0000 285.0000 12.62190680 403
**GLOB0706**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 270.0000 0010000 0.0000 345.0000 12.62190680 411
**GLOB0801**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 315.0000 0010000 0.0000 52.5000 12.62190680 422
**GLOB0802**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 315.0000 0010000 0.0000 112.5000 12.62190680 430
**GLOB0803**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 315.0000 0010000 0.0000 172.5000 12.62190680 447
**GLOB0804**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 315.0000 0010000 0.0000 232.5000 12.62190680 455
**GLOB0805**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 315.0000 0010000 0.0000 292.5000 12.62190680 462
**GLOB0806**
1 00000R 93 51.00000000 .00000000 00000-0 00000-0 0 1
2 00000 52.0000 315.0000 0010000 0.0000 352.5000 12.62190680 470

## Table A1-2
## Orbital Elements for the GPS Constellation Satellites

**GPS BII-01**
1 19802U 89 13 A 93 49.10411581 .00000015 00000-0 99999-4 0 5695
2 19802 55.0565 158.8784 0040031 173.1610 186.8719 2.00574085 29345
**GPS BII-02**
1 20061U 89 44 A 93 48.94918932 -.00000032 00000-0 99999-4 0 5747
2 20061 54.8540 336.1810 0116917 201.1199 158.1734 2.00560512 27084
**GPS BII-03**
1 20185U 89 64 A 93 49.28554523 .00000015 00000-0 99999-4 0 5195
2 20185 54.8814 159.5718 0009687 199.1573 160.7870 2.00572086 25667
**GPS BII-04**
1 20302U 89 85 A 93 48.81568417 -.00000011 00000-0 99999-4 0 5157
2 20302 53.8978 276.8983 0013087 336.4604 23.5409 2.00555610 24459
**GPS BII-05**
1 20361U 89 97 A 93 48.33292414 .00000005 00000-0 99999-4 0 4660
2 20361 55.2743 101.5872 0071864 94.0294 266.8594 2.00564631 13920
**GPS BII-06**
1 20452U 90 8 A 93 48.73063905 .00000010 00000-0 99999-4 0 5162
2 20452 54.1286 216.2286 0050822 66.1480 294.3595 2.00575035 22435
**GPS BII-07**
1 20533U 90 25 A 93 49.13744314 -.00000031 00000-0 99999-4 0 5160
2 20533 55.1856 336.5450 0039349 84.8741 275.5872 2.00574777 21212
**GPS BII-08**
1 20724U 90 68 A 93 48.46065677 .00000015 00000-0 99999-4 0 4173
2 20724 54.6868 157.3596 0101220 147.1688 213.4503 2.00563525 18624
**GPS BII-09**
1 20830U 90 88 A 93 49.01121131 .00000004 00000-0 99999-4 0 4654
2 20830 55.1904 99.6468 0067077 109.1052 251.6935 2.00567264 17715
**GPS BII-10**
1 20959U 90103 A 93 47.91749227 .00000015 00000-0 99999-4 0 3621
2 20959 54.9083 159.1712 0067665 218.6043 140.8912 2.00559783 16287
**GPS BII-11**
1 21552U 91 47 A 93 49.18210886 .00000003 00000-0 99999-4 0 3171
2 21552 55.4984 97.0681 0046554 232.6688 126.9790 2.00560960 11905
**GPS BII-12**
1 21890U 92 9 A 93 49.15003794 -.00000011 00000-0 99999-4 0 2157
2 21890 54.4503 276.6586 0057950 147.9419 212.4672 2.00552492 7273
**GPS BII-13**
1 21930U 92 19 A 93 45.86483263 -.00000022 00000-0 99999-4 0 2051
2 21930 55.3401 37.3993 0069456 163.6553 196.5863 2.00560759 6130
**GPS BII-14**
1 22014U 92 39 A 93 44.40492607 .00000011 00000-0 99999-4 0 1065
2 22014 54.9921 217.2297 0080376 282.9048 76.2088 2.00559492 4436
**GPS BII-15**
1 22108U 92 58 A 93 48.86019890 -.00000011 00000-0 99999-4 0 1154
2 22108 54.6058 277.2606 0104337 121.8841 239.1811 2.00560986 3213
**GPS BII-16**
1 22231U 92 79 A 93 40.57268866 .00000010 00000-0 99999-4 0 363
2 22231 54.8083 218.6759 0039885 299.7948 59.7907 2.00556797 1626
**GPS BII-17**
1 22275U 92 89 A 93 37.71362322 .00000011 00000-0 99999-4 0 165
2 22275 54.7396 216.3573 0054045 259.2098 100.1129 2.00564739 970
**GPS BII-18**
1 22446U 93 7 A 93 47.26743718 -.00000032 00000-0 99999-4 0 163
2 22446 54.8506 337.1100 0065011 329.5938 30.0276 2.00576471 195

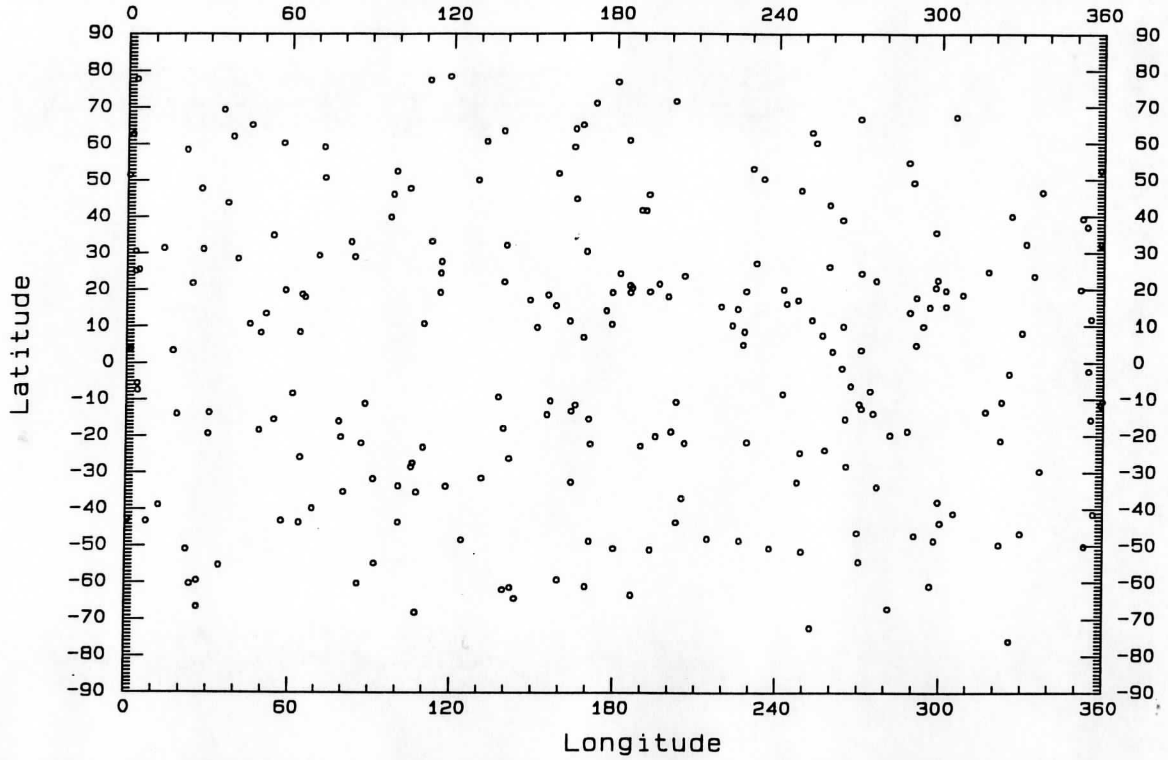


**Figure A1-1. Plot of the geographic entry occultation locations for a Globalstar satellite versus all GPS satellites.**

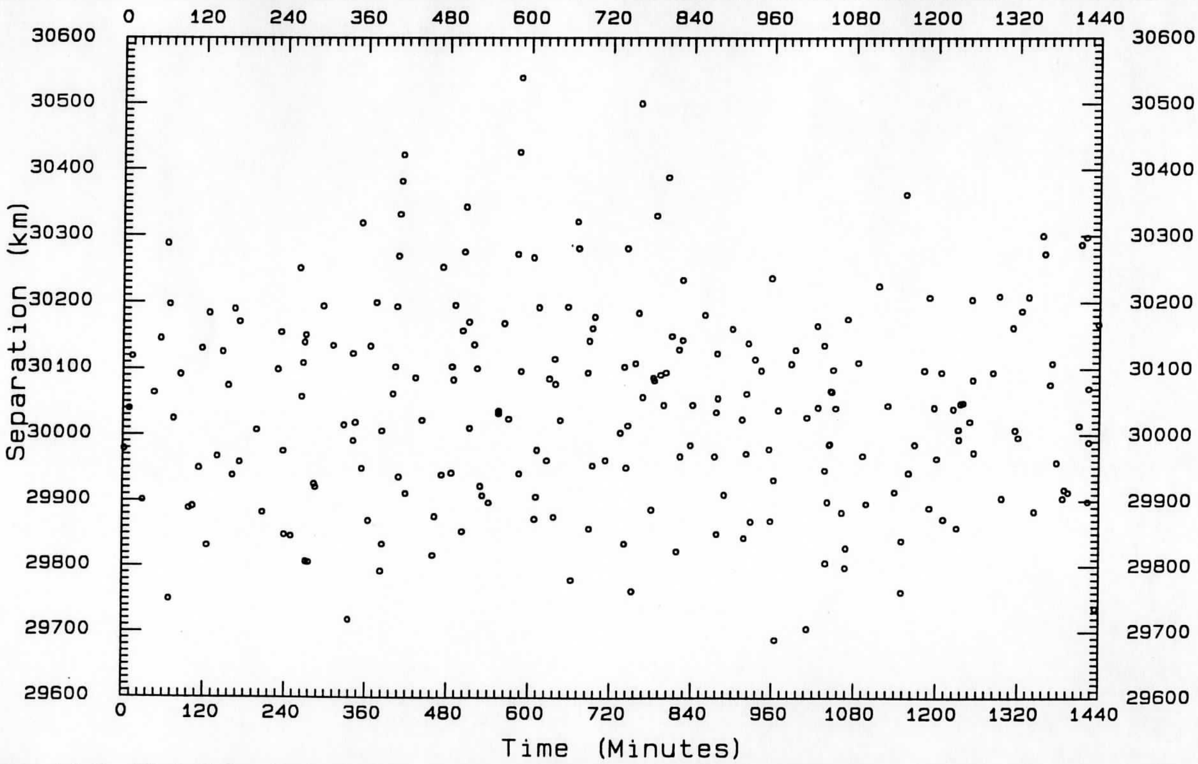


**Figure A1-2. Plot of the distances for entry occultations between a Globalstar satellite versus all GPS satellites.**

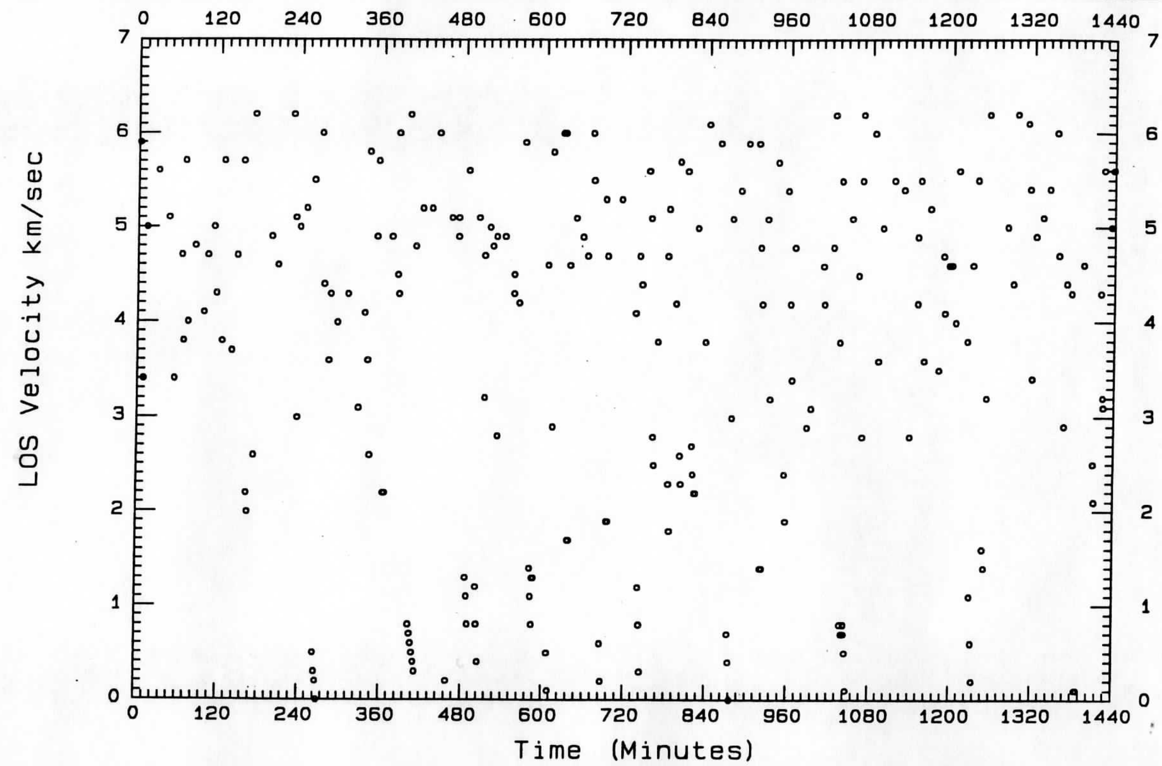


Figure A1-3. Plot of the doppler velocities for a Globalstar satellite versus all GPS satellites during entry occultations.

## Appendix 2
## Error Analysis for Water Vapor Measurements

This error analysis is concerned with the propagation of uncertainties in the transmitted and received powers into the retrieved values of column water vapor amounts. We do not here derive link errors, but show how assumed link errors affect the retrieved data product.

We follow two approaches: (1) we compute an exact relationship between measurement errors and the error in $u$ and evaluate it by monte carlo techniques; and (2) we derive an approximate relationship that can be evaluated analytically. The two results are seen to be very similar.

1. *Exact Expression*

Recalling that the integrated column water amount is related to $S$ by equation (6), we first consider how uncertainties in power affect $S$. Taking the logarithm of Eq. (2), and introducing fractional errors $\varepsilon$ for transmitted and received powers, we can write the measured value of $S$ in the form

$$S_m(\theta) = -\ln\left[\frac{P_r(f_l,\theta,\phi)(1\pm\varepsilon_r^l)/\left[P_t(f_l)G(f_l,\theta,\phi)(1\pm\varepsilon_t^l)\right]}{P_r(f_o,\theta,\phi)(1\pm\varepsilon_r^o)/\left[P_t(f_o)G(f_o,\theta,\phi)(1\pm\varepsilon_t^o)\right]}\right] \quad \text{(A2-1)}$$

where $\varepsilon$ has superscripts denoting on-line ($l$) or off-line ($o$) errors, and subscripts denoting transmitter ($t$) or receiver errors ($r$). (Here we have lumped the antenna gain factor uncertainty into the fractional error in transmitted power.) Collecting fractional error factors, and making use of Eq. (2), the above equation can be rewritten in the form

$$S_m(\theta) = -\ln\left[\frac{\tau(f_l,\theta)(1\pm\varepsilon_r^l)(1\pm\varepsilon_t^o)}{\tau(f_o,\theta)(1\pm\varepsilon_r^o)(1\pm\varepsilon_t^l)}\right] \quad \text{(A2-2)}$$

Writing the log of factors as the sum of logs, yields the more useful expression

$$S_m(\theta) = S(\theta) - \ln\left[\frac{(1\pm\varepsilon_r^l)(1\pm\varepsilon_t^o)}{(1\pm\varepsilon_r^o)(1\pm\varepsilon_t^l)}\right] \quad \text{(A2-3)}$$

The change in total column water corresponding to the measurement deviation from the true value of S is given by

$$\delta u = \frac{S(\theta)_m - S(\theta)}{\bar{k}\sec(\theta)} \quad \text{(A2-4)}$$

so that the fractional error in u, then takes the form

$$\frac{\delta u}{u} = \ln\left[\frac{(1\pm\varepsilon_r^l)(1\pm\varepsilon_t^o)}{(1\pm\varepsilon_r^o)(1\pm\varepsilon_t^l)}\right] / \left[\bar{k}u\sec(\theta)\right] \quad \text{(A2-5)}$$

Considering a statistical ensemble of $M$ cases, the expectation value of the fractional error can be written as

$$E\left[\frac{\delta u}{u}\right] = \sqrt{\frac{1}{M}\sum\left(\frac{\delta u}{u} - \left\langle\frac{\delta u}{u}\right\rangle\right)^2} \quad \text{"Exact Formulation"} \quad \text{(A2-6)}$$

$E\left[\frac{\delta u}{u}\right]$ can be determined numerically from retrieval simulations using a random number generator to produce the transmitter/ receiver errors.

2. *Approximate Equation*

For small x, ln(1+x)≈x. Thus we can write Eq. (A2-5) in the approximate form

$$\frac{\delta u}{u} \cong \left[ \frac{\pm\varepsilon_r^{\ell} \pm \varepsilon_t^{o} \mp \varepsilon_r^{o} \mp \varepsilon_t^{\ell}}{\overline{k}' u \sec(\theta)} \right] \qquad \text{(A2-7)}$$

from which we can determine the expected average value for an infinite statistical sample of cases, namely

$$E\left[\frac{\delta u}{u}\right] \cong \frac{\sqrt{\sigma_{\ell r}^2 + \sigma_{ot}^2 + \sigma_{or}^2 + \sigma_{\ell t}^2}}{\overline{k}' u \sec(\theta)} \qquad \text{"Approximate Formula"} \quad \text{(A2-8)}$$

It is shown in the following section that the error of the approximation is generally less than 2%.

3. *Results of the Error Analysis*

The table below gives the values of parameters used to conduct the analysis of the total water content retrieval error. Plots of *u, S*, and the vertical mean *k'*, are provided in Figures 4a, 4b, and 4c respectively.

| | *k'* | *u* | *k'u* | τ(22.5) | τ(19.2/25.8) |
|---|---|---|---|---|---|
| Tropical | 1.2186 | 0.13760 | 0.16768 | 0.745 | 0.881 |
| Mid Lat. Summer | 1.2598 | 0.09776 | 0.12316 | 0.804 | 0.909 |
| Sub Arctic Summer | 1.3060 | 0.06962 | 0.09092 | 0.847 | 0.929 |
| US Std Atm | 1.3280 | 0.04737 | 0.06921 | 0.887 | 0.945 |
| Mid Lat Winter | 1.2801 | 0.02849 | 0.03647 | 0.993 | 0.957 |
| Sub Arctic Winter | 1.2963 | 0.01392 | 0.01804 | 0.950 | 0.967 |
| **MEAN** | 1.28 | 0.066 | 0.084 | 0.870 | 0.931 |

For each of the atmospheres in the above table, we used a monte carlo calculation of 10,000 random receiver (r) and transmitter (t) error situations to produce the total water vapor content retrieval errors using Equation (A2-6). We also computed the approximate error for each atmosphere using the approximation given by Equation (A2-8). The results are presented in the following table.

**Comparison of Exact vs. Approximate Formula**

| Error(*r/t*) | 1%/1% | | 0.5%/5% | | 0%/3% | |
|---|---|---|---|---|---|---|
| Air Mass | Exact | Approx | Exact | Approx | Exact | Approx |
| **T** | 0.118 | 0.119 | 0.427 | 0.424 | 0.255 | 0.253 |
| **MS** | 0.161 | 0.162 | 0.582 | 0.577 | 0.347 | 0.345 |
| **SS** | 0.218 | 0.220 | 0.790 | 0.782 | 0.470 | 0.467 |
| **US** | 0.315 | 0.289 | 1.144 | 1.027 | 0.681 | 0.613 |
| **MW** | 0.543 | 0.548 | 1.982 | 1.948 | 1.178 | 1.163 |
| **SW** | 1.096 | 1.109 | 4.053 | 3.939 | 2.402 | 2.352 |

4. *Simplified Expression for the Total Error*

It follows from the above "approximate" retrieval error (Eqn. 15) that

$$E\left[\frac{\delta u}{u}\right] \cong \frac{\sqrt{2}\sqrt{\sigma_t^2 + \sigma_r^2}}{\sqrt{N}\,\bar{k}\,u\sec(\theta)} = K\sigma_{sys} \qquad \text{(A2-9)}$$

where $\sigma_{sys}$ =the total transmitter/receiver system noise and *N* is the number of independent measurement samples. For *N*=100 (e.g. 1 sample/sec as the satellite orbits overhead) and $\bar{k}\,u\sec(\theta)$ =(0.084)(1.5)=0.127, we obtain

$$E\left[\frac{\delta u}{u}\right] \cong \frac{7.9}{\sqrt{N}}\sigma_{sys} = 0.8\sigma_{sys} \qquad \text{(A2-10)}$$

Thus 10% system noise ⇒ 8% error in *u*.

5. *Systematic Errors Eliminated By Angle Scanning*

Consider two angles $\theta$ and $\theta_2$. Then

$$u\sec(\theta_1) + \varepsilon = \frac{S(\theta_1) + E(s)}{\bar{k}'} \qquad \text{(A2-11)}$$

$$u\sec(\theta_2) + \varepsilon = \frac{S(\theta_2) + E(s)}{\bar{k}'} \qquad \text{(A2-12)}$$

where $\varepsilon = \frac{E(s)}{\bar{k}'}$. Subtracting (A2-11) from (A2-12) leads to

$$u = \frac{S(\theta_1) - S(\theta_2)}{\bar{k}'(\sec(\theta_1) - \sec(\theta_2))} \qquad \text{(A2-13)}$$

which is independent of any systematic error *E*(*s*).

6. *Horizontal Homogeneity Check*

Use of the above expression (Eq. 20) to eliminate any systematic error component of *S* requires that the atmosphere be horizontally stratified between angles $\theta$ and $\theta_2$. This can be verified using an intermediate angle , $\theta_0$, and ensuring that

$$\frac{S(\theta_1) - S(\theta_0)}{S(\theta_2) - S(\theta_0)} \le \frac{\sec(\theta_1) - \sec(\theta_0)}{\sec(\theta_2) - \sec(\theta_0)} + \varepsilon^* \qquad \text{(A2-14)}$$

where $\varepsilon^*$ is an inhomogeneity error tolerance.

## Appendix 3

## Accounting for Minor Variations of $\overline{k}'$

As shown in Figure III.4, as much as 5% error in *u* can result from the synoptic variability of *k'*. This small error can be corrected using the procedure described below.

Climatological averages of water vapor profiles (e.g. monthly means) have the form

$$q = q_0 (P / P_0)^{\lambda} \quad \text{(A3-1)}$$

so that

$$\overline{k}' = \frac{\lambda + 1}{P_0} \int_0^{P_0} k' (P / P_0)^{\lambda} dp \quad \text{(A3-2)}$$

Seasonal and latitudinal mean values of $\lambda$, according to Smith (1966), are provided in the following table.

| Latitude Zone (N) | Winter | Spring | Summer | Fall | Annual Average |
|---|---|---|---|---|---|
| 0-10 | 3.37 | 2.85 | 2.80 | 2.64 | 2.91 |
| 10-20 | 2.99 | 3.02 | 2.70 | 2.93 | 2.91 |
| 20-30 | 3.6 | 3.00 | 2.98 | 2.93 | 3.12 |
| 30-40 | 3.04 | 3.11 | 2.92 | 2.94 | 3.00 |
| 40-50 | 2.7 | 2.95 | 2.77 | 2.71 | 2.78 |
| 50-60 | 2.52 | 3.07 | 2.67 | 2.93 | 2.79 |
| 60-70 | 1.76 | 2.69 | 2.61 | 2.61 | 2.41 |
| 70-80 | 1.60 | 1.67 | 2.24 | 2.63 | 2.03 |
| 80-90 | 1.11 | 1.44 | 1.94 | 2.02 | 1.62 |
| Hemisphere Average | 2.52 | 2.64 | 2.62 | 2.7 | 2.61 |

Since

$$u = \frac{1}{g} \int_0^{P_0} q dp = \frac{q_0 P_0}{g(\lambda + 1)} \quad \text{(A3-3)}$$

We can provide an nth estimate of $\lambda$ from an (n-1)th estimate of *u* given an in-situ measurement of $q_0$ and $p_0$ at the receiver.

That is

$$\lambda^n = \frac{q_0 p_0}{g u^{n-1}} - 1. \quad \text{(A3-4)}$$

The processing procedure that would converge to a corrected value of total column water vapor is summarized by the following steps:

(1) Obtain $k'$ and $u$ initially using climatological value of λ ($\bar{k}' = \frac{\lambda+1}{P_0}\int_0^{P_0} k'(P/P_0)^{\lambda} d$ and

$u = \frac{S(\theta)}{\bar{k}' \sec(\theta)}$)

(2) Obtain improved estimate of λ (λ= ($q_0 p_0/gu$)-1).

(3) Iterate Steps (1) and (2) as needed.