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Jimsphere and Radar Wind Profiler Turbulence Indicators

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The primary objective of this paper is to report on the research and technology in identifying wind and turbulent regions from the surface to 16 km (9.94 mi) by the FPS-16 radar/Jimpshere system and to use these wind and turbulent assessments to validate NASA's 50-MHz Radar Wind Profiler. Eleven wind profiles obtained from two Space Shuttle launches, STS-37 and STS-43, during the day of launch were compared. Comparative measurements of the Jimsphere and the Wind Profiler for the vertical gradient (turbulence), Richardson number, stability parameter, scalar wind, and the turbulence probability index show very good agreement between the two sensors. Wind profile statistics from the two wind sensors were compared at a 150-m wavelength. This important calculation of 150-m wavelength was obtained by computing autospectra, cross-spectra, and coherence squared spectra from 20 Jimsphere balloons tracked simultaneously by FPQ-14 and FPS-16 radars. It is further demonstrated that the prototype wind profiler is an excellent monitoring device illustrating the measurements of the winds within 1/2 h of launch zero (L-O). This fills in the time gap of wind profiles closer to L-O because during the Space Shuttle launches, the ascent wind loads are computed 2 h before launch, based on winds aloft obtained by the Jimsphere 2.0 h before liftoff. This increases the probability of a successful mission.

Nomenclature

A	=	wind directional shear, deg/s
B	=	change in temperature lapse rate, 1/s
dV/dH	=	vertical wind shear measurement, 1/s
g	=	acceleration of gravity, m/s^2
H	=	scale height, 150 m
k	=	Von Karman's constant, 0.47
R_i	=	Richardson number
S	=	wind speed, m/s
T	=	temperature, K
T_i	=	turbulence probability indicator, 1/s^2
U_*	=	turbulent stress, m/s
u',v',w'	=	zonal, meridional, and vertical velocity perturbations, m/s
V_g	=	vertical gradient (turbulence), m/s^2
X	=	scale height, 150 m
Δ^2T/m	=	second difference operator of temperatures, deg/m
ΔZ	=	scale length, m
$\Delta\alpha$	=	change on wind direction, deg
$\partial T/\partial Z$	=	vertical temperature gradient, K/km
$\partial V/\partial Z$	=	vertical shear of horizontal winds, 1/s
Γ	=	dry adiabatic lapse rate, 9.8 K/km
ξ	=	stability parameter

Introduction

THE existing technology for the past three decades ('60's, '70's, and '80's), and the present decade, in measuring winds aloft for the Saturn–Apollo Space Vehicles and the Space Shuttle launches has consisted of obtaining the necessary data by balloon-borne wind sensors, e.g., the FPS-16 radar/Jimsphere system (used as the standard) and the meteorological sounding system (MSS) windsonde (used as the backup). The wind profiles are measured in the lower stratosphere and troposphere of the atmosphere, 0–16 km (0–9.94 miles), for the wind load analysis of the ascent phase of the Space Shuttle as it passes through max q (maximum dynamic pressure) where the loads are the greatest on the vehicle.

Electromagnetic probing of the atmosphere by clear-air radars is an emerging technology used to supplement balloon-borne wind sensors which are used to determine ascent wind loads on the Space Shuttle, which was documented by Susko[1] in his report "Wind Measurements by Electromagnetic Probes." Electromagnetic probes of the atmosphere used to measure the velocity of winds are based on the Doppler effect. The Doppler effect is a change in frequency of the electromagnetic wave reflected back toward the receiver when the receiver and the reflecting region are in motion relative to one another. The technique of using Doppler anemometry is based on the fact that electromagnetic signals, passing through a fluid, are scattered by tracers in the fluid. In the case of laser Doppler systems, the scattering occurs from the particles suspended in the fluid, in microwave radars, from hydrometers.

The scattered radiation contains information on the velocity of the tracers from which the radiation was scattered. The information on the velocity of the tracer manifests itself by frequency shifting the tracer. The amount that the source frequency is shifted, Δf, upon striking the tracer and returning to a receiver is called the Doppler shift or Doppler frequency.[2]

Doppler radar systems have been used for a number of years to measure atmospheric motions by scattering from hydrometers.[3–6] A variety of techniques have been devised for observing precipitation and motions within clouds. These techniques have been developed and measure not only wind velocity components, but also such quantities as wind divergence and deformation.

Description of the 50-MHz Radar Wind Profiler and Jimsphere

Currently at the Kennedy Space Center (KSC), Wilfong et al.[7] reported on the operation and monitoring of the winds aloft as input to launch operations for the Space Shuttle launches. Also, reporting on the differences between the FPS-16 Radar/Jimsphere System and the 50-MHz Radar Wind Profiler was Lapenta.[8] The differences reported may be due to the temporal and spatial difference in the measurement systems. The temporal differences result from different measurement techniques. The Radar Wind Profiler will obtain a new wind profile on the

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order of every 30 min based on a consensus average of 10 wind profiles measured every 3 min at a height interval of 150 m–20 km.[7] The Jimsphere measurement is an instantaneous measurement. The Jimsphere rise rate of 5 m/s takes over 50 min to reach 16 km.

The spatial difference between the two launch sites at KSC is approximately 20 km (12.5 miles).[8] The wind profiler beams are stationary and the balloon is not. Thus, depending on the speed and direction of the upper-level winds, the Jimsphere balloon can be transported downstream up to 100 km (62 miles from the Cape Canaveral balloon facility[1,8]).

Data from the Jimsphere system are calculated every 30 m and averaged over a scale length of 150 m in altitude. The length scale was made at 150-m intervals because the discernible wavelengths of the Jimsphere are on the order of 100–150 m as noted by Endlich et al.[9] and Smith.[10]

Therefore Radar Wind Profiler wind data are computed for a length scale every 150 m and averaged over 30 m, while the Jimsphere is computed for 30 m. Thus, all the figures presented in this paper: vertical gradient (turbulence), Richardson number, stability parameter, scalar winds, and turbulence probability index are plotted and compared every 30 m for the two wind sensors based on the 150-m wavelength obtained from the spectral analysis.

The meteorological data error estimates for the Jimsphere are: wind speed, surface to 18 km (60-m mean layer winds)

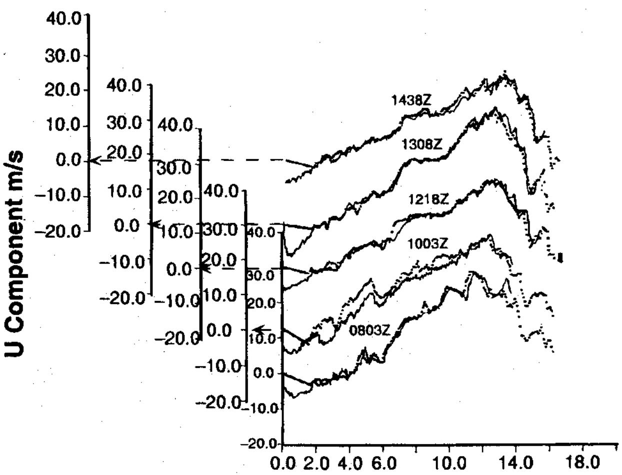

Fig. 1 Five-u wind components of the NASA 50-MHz radar wind profiler overlayed on the wind profile of FPS-16 radar/jimsphere measured during the STS-37 launch, April 5, 1991, at KSC, Florida.

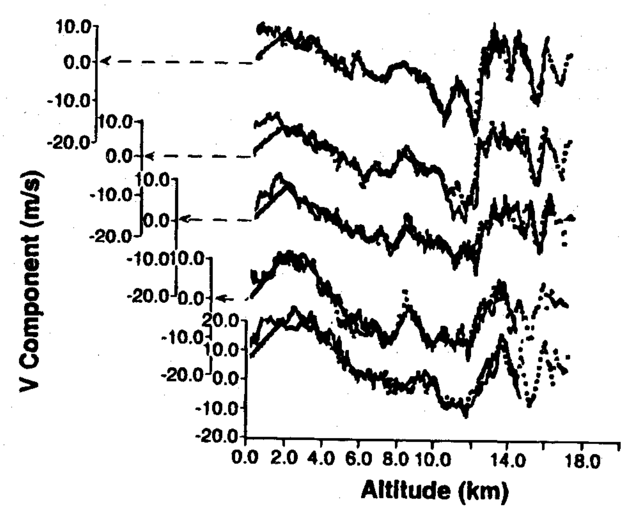

Fig. 2 Five v-wind components of the NASA 50-MHz radar wind profiler overlayed on the wind profile of FPS-16 radar/jimsphere measured during the STS-37 launch, April 5, 1991, at KSC, Florida.

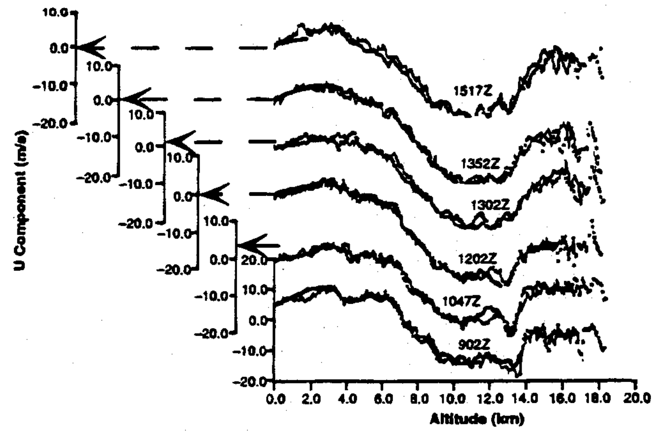

Fig. 3 Six u-wind components of the NASA 50-MHz radar wind profiler overlayed on the wind profile of the FPS-16 radar/jimsphere measured during the STS-43 launch, August 2, 1991, at KSC, Florida.

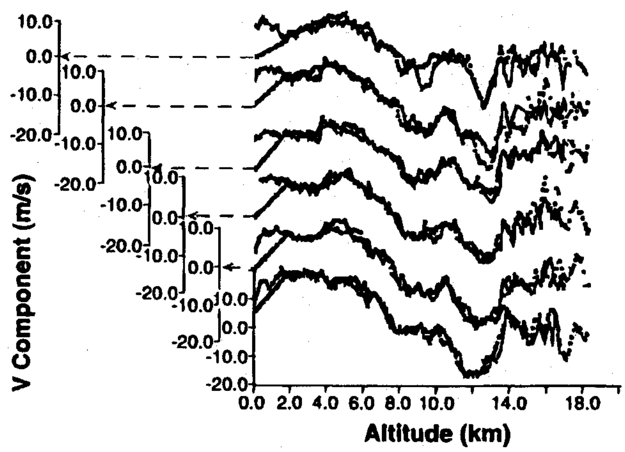

Fig. 4 Six v-wind components of the NASA-50 MHz radar wind profiler overlayed on the wind profile of the FPS-16 radar/jimsphere measured during the STS-43 launch, August 2, 1991, at KSC, Florida.

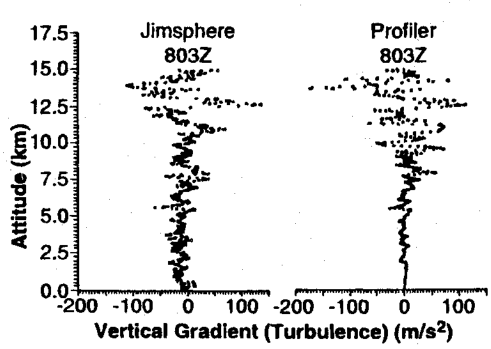

Fig. 5 Comparison of the vertical gradient (turbulence) winds aloft for the jimsphere and wind profiler, April 5, 1991 (0803Z), during launch of STS-37.

0.3-m/s vertical error estimate; temperature varies linearly with altitude from 0.4°C at the surface to 1.8°C at 30 km; wind direction, 0–360 deg, 2 deg.[11] Measurements of the meteorological parameters of wind and wind direction were made by the Jimsphere and rawinsonde for temperature.

Spectral Analysis of the Jimsphere

To assist in the validation of the Radar Wind Profiler and to obtain a wavelength for comparative purposes, further studies of the dual-tracked Jimsphere data series were analyzed to determine the noise level in Jimsphere measurements that had been causing design curve exceedances (Smith[10]). Spectra and cross-spectra of the profiles for all 20 pairs were computed and averaged. If it is postulated that the measurements are composed of the wind plus independent radar noise, averaging is required to cause the autospectral estimates to converge to the spectra of the actual wind plus the spectra of white noise.

The information in the three spectral amplitude curves can be summarized by computing the quantity known as coherence squared. This quantity is effectively a correlation coefficient presented as a function of wave number (1/wavelength). Coherence squared is the ratio of the magnitude of the cross-spectra squared to the product of the FPS-16 and the FPQ-14 radars of the autospectra, which can be approximated by the ratio of signal-to-signal plus noise.

The signal equals the noise power spectral density at a wavelength of approximately 150 m for the u component and approximately 300 m for the v component. This discrepancy between wind components is probably due to the fact that the wind

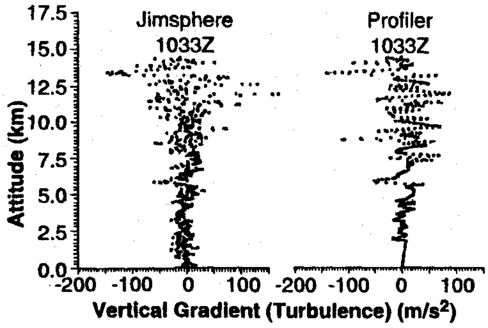

Fig. 6 Comparison of the vertical gradient (turbulence) winds aloft for the jimsphere and wind profiler, April 5, 1991 (1033Z), during launch of STS-37.

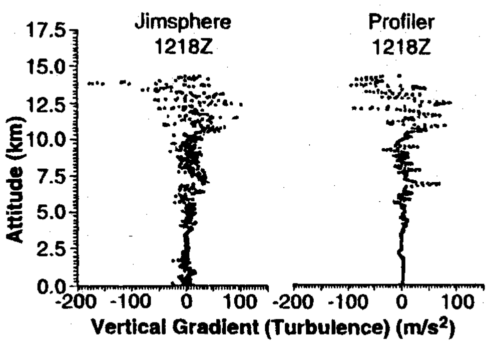

Fig. 7 Comparison of the vertical gradient (turbulence) winds aloft from the jimsphere and wind profiler, April 5, 1991 (1218Z), during launch of STS-37.

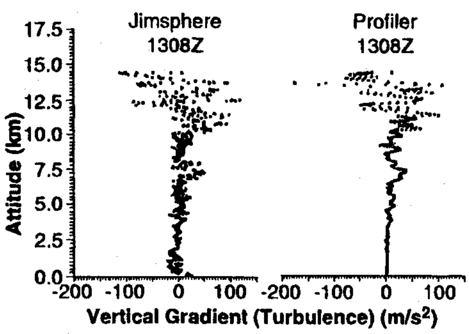

Fig. 8 Comparison of the vertical gradient (turbulence) winds aloft for the jimsphere and wind profiler, April 5, 1991 (1308Z), during launch of STS-37.

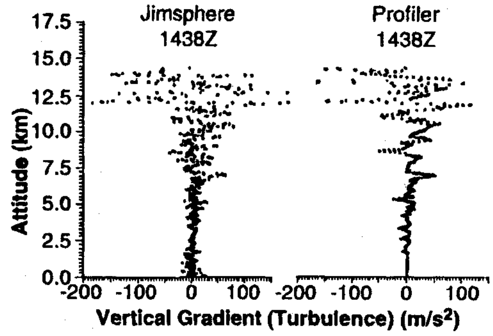

Fig. 9 Comparison of the vertical gradient (turbulence) winds aloft for the jimsphere and wind profiler, April 5, 1991 (1438Z), during launch of STS-37.

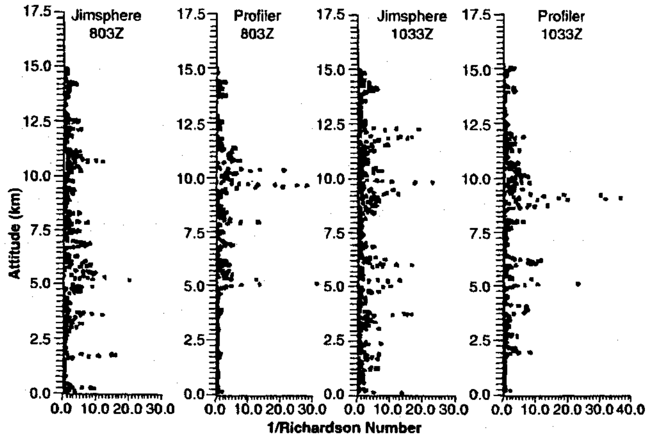

Fig. 10 Comparison of 1/Richardson number winds aloft for the jimsphere and wind profiler, April 5, 1991 (0803Z and 1033Z), during launch of STS-37.

blows mainly toward the east at KSC. The u component is determined primarily by changes in the radar measurements of elevation angle and range to the Jimsphere. The v component is determined by changes in three measurements: range, elevation angle, and azimuth angle. With an additional source of noise (azimuth angle), more noise is expected in the v component of the wind.

Comparison of Jimsphere vs Radar Wind Profiler Wind Components

A comparison of the u and v wind components for the FPS-16 Radar/Jimsphere Balloon System and NASA's 50-MHz Radar Wind Profiler is presented in Figs. 1–4 for two Space Shuttle launches, STS-37 (Atlantis) on April 5, 1991 and STS-43 (Atlantis) on August 2, 1991. From KSC on STS-37's day of launch, five Jimsphere/Profiler wind profile data sets were compared at 0803Z, 1033Z, 1218Z, 1308Z, and 1438Z. The standard deviation of the differences for the u wind component was 1.94 m/s and 1.67 m/s for the v wind component as illustrated in Figs. 1 and 2. The Radar Wind Profiler wind data are computed for a length scale every 150 m and averaged over 30 m, while the Jimsphere is computed for 30 m. Thus, the Jimsphere/Profiler wind profile data sets are plotted and compared every 30 m in Figs. 1–4. Figures 3 and 4 illustrate the u and v components comparison of winds aloft during STS-43 launch. Six Jimsphere/Profiler wind data sets were compared at 0902Z, 1047Z, 1202Z 1302Z, 1352Z, and 1517Z. The standard deviation for u wind component differences was 1.39 m/s and 1.46 m/s for the v wind component.

Vertical Gradient (Turbulence) Comparison

One meteorological parameter used in describing the dynamics of turbulence is the vertical gradient (turbulence) (V_g) as

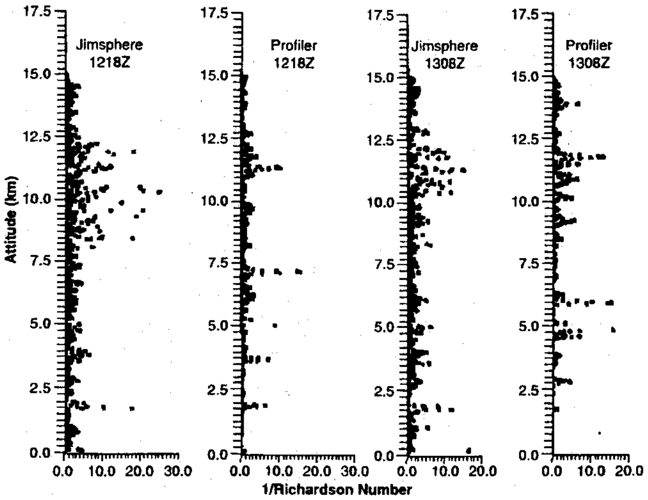

Fig. 11 Comparison of 1/Richardson number winds aloft for the jimsphere and wind profiler, April 5, 1991 (1218Z and 1308Z), during launch of STS-37.

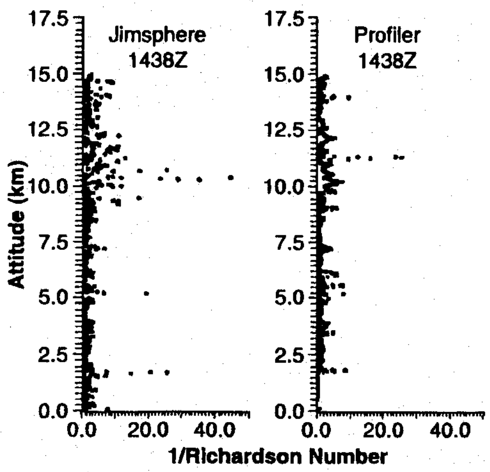

Fig. 12 Comparison of 1/Richardson number winds aloft for the jimsphere and wind profiler, April 5, 1991 (1438Z), during launch of STS-37.

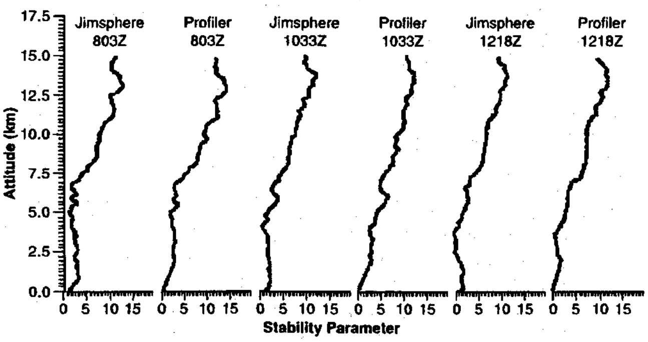

Fig. 13 Comparison of the stability parameter winds aloft for the jimsphere and wind profiler, April 5, 1991 (0803Z, 1033Z, and 1218Z), during launch of STS-37.

reported by Ehernberger.[12] The value of the vertical gradient (turbulence) has been derived as the product of wind speed (V) and vertical wind shear measurements ($\mathrm{d}V/\mathrm{d}H$) obtained directly from Jimsphere data. The equation is

$$Vg = V\mathrm{d}V/\mathrm{d}H \tag{1}$$

Figures 5–9 illustrate the comparison of Jimsphere vs Profiler plots for times 0803Z, 1033Z, 1218Z, 1308Z, and 1438Z for the STS-37 launch on April 5, 1991, at KSC, Florida. Notice the similarity in the data comparison between the Jimsphere and the Profiler in in Figs. 5–9.

Richardson Number Comparison

From the rawinsonde data obtained from the meteorological section, Cape Canaveral Air Force Station, Florida, which consists of winds, temperature, and pressure as a function of altitude and the winds from the Jimsphere, the Richardson number (Ri), a stability criteria for determining the presence or absence of atmospheric turbulence, was computed and is given by the following relationship:

$$R_i = \frac{g}{T}\left[\frac{\partial T}{\partial Z} + \Gamma\right] \Big/ \left[\frac{\partial V}{\partial Z}\right]^2 \tag{2}$$

where g is the acceleration of gravity, $\partial T/\partial Z$ is the vertical temperature gradient, Γ is the dry adiabatic lapse rate (= 9.8 K/km), and

$$\left[\frac{\partial V}{\partial Z}\right]^2 = \left[\frac{\partial V_x}{\partial Z}\right]^2 + \left[\frac{\partial V_y}{\partial Z}\right]^2 \tag{3}$$

is the square of the vertical shear of the horizontal winds.

The Richardson number was calculated for the five wind profiles during the launch of STS-37 on April 5, 1991, from KSC, Florida. Comparison of Jimsphere vs the Wind Profiler are given in Figs. 10–12 for times 0803Z, 1033Z, 1218Z, 1308Z, and 1438Z.

Since instabilities of turbulence increase when the Richardson number decreases to a value near 0.25, the Richardson number was inverted for clarity, indicating turbulence with the larger numbers.

Stability Parameter Comparison

The stability parameter (ξ), obtained from the Jimsphere balloon wind measurements and the temperature from the rawinsonde, was calculated from the equation $\xi = X/L$ where X is the scale height as reported in Ref. 13 and

$$L = \frac{\overline{T}U^3 *}{kg\ \overline{w'T'}} \tag{4}$$

where the stress parameter, $U^2 *$ is

$$U^2 * = \sqrt{(\overline{u'w'})^2 + (\overline{v'w'})^2} \tag{5}$$

T is the temperature in degrees K, k is Von Karman's constant, w' is the vertical velocity perturbation, g is the acceleration of gravity. Figures 13 and illustrate the stability parameter for the

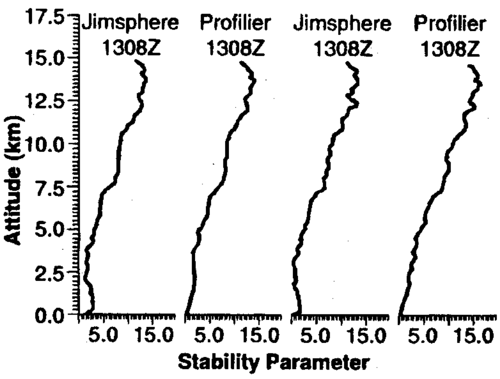

Fig. 14 Comparison of the stability parameter winds aloft for the jimsphere and wind profiler, April 5, 1991 (1308Z and 1438Z), during launch of STS-37.

launch of STS-37 on April 5, 1991. Notice the fairly consistent repetitive perturbations in comparing the Jimsphere/Profiler wind data for the five winds aloft data sets.

Scaler Winds Profile Comparison

Figure 15 illustrates the comparison of the Jimsphere/Profiler winds aloft during the launch of STS-37 on April 5, 1991, at KSC, Florida. The pairs of Jimsphere and Wind Profiler wind

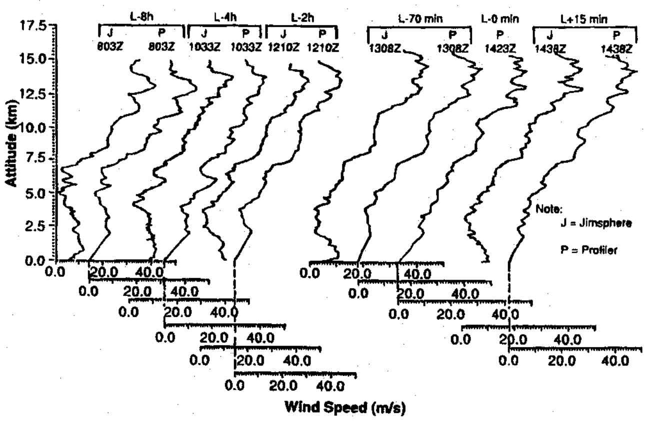

Fig. 15 Comparison of the scalar wind speed for the jimsphere and the wind profiler, April 5, 1991 (0803Z, 1033Z, 1218Z, 1308Z, and 1438Z), during launch of STS-37.

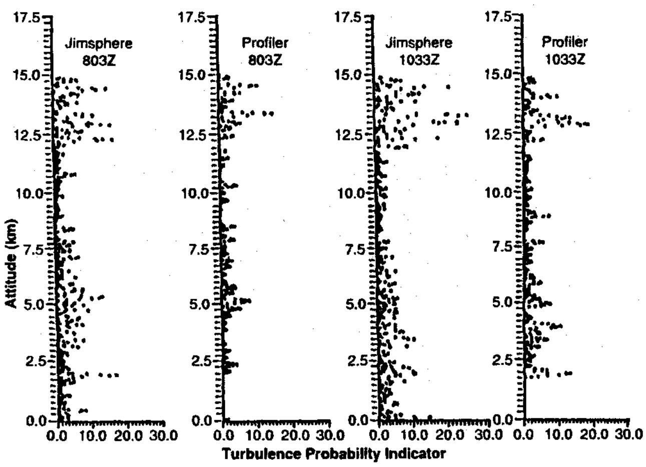

Fig. 16 Comparison of the turbulence probability indicator for the jimsphere and wind profiler, April 5, 1991 (0803Z and 1033Z) during launch of STS-37.

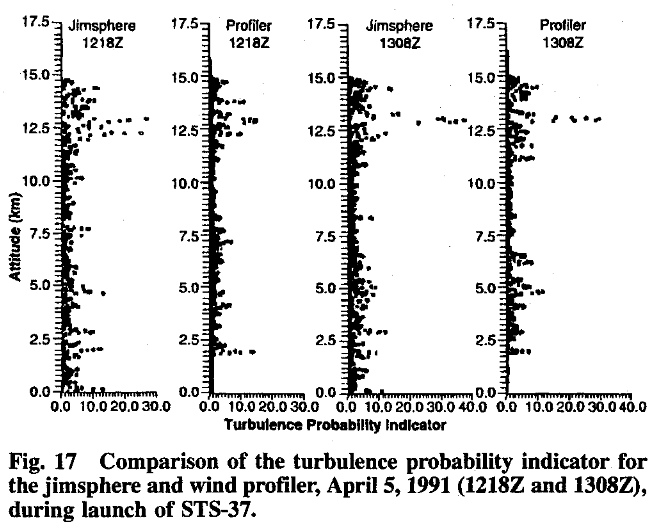

Fig. 17 Comparison of the turbulence probability indicator for the jimsphere and wind profiler, April 5, 1991 (1218Z and 1308Z), during launch of STS-37.

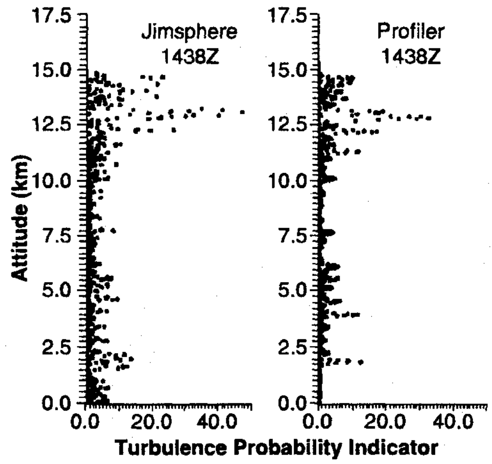

Fig. 18 Comparison of the turbulence probability indicator for the jimsphere and wind profiler, April 5, 1991 (1438Z), during launch of STS-37.

profile were compared at 0803Z, 1033Z, 1218Z, 1308Z, and 1438Z. The figures show the buildup and backoff fluctuations occurring simultaneously in both wind sensors. Further details on turbulence and wind indicators for Space Shuttle launches are presented in Ref. 14.

Turbulence Probability Index Comparison

Turbulence probability index (T_i) was reported by Endlich et al.,[9] and further defined in Ref. 15 where $T_i = A\ B$.

Factor A, which is the wind directional shear, is given by the equation

$$A = S|\Delta\alpha/\Delta z| \tag{6}$$

where S is wind speed and $\Delta\alpha$ is the change in wind direction over the scale length of Δz.

The second factor B is equal to the change in temperature lapse rate. The equation is

$$B = [(g/T)|\Delta^2 T/\Delta z|]^{1/2} \tag{7}$$

where$g$ is the acceleration of gravity and $\Delta^2 T$ is the second difference operator of the temperature T. The two factors are multiplied together, resulting in $T_i = AB$.

Figures 16–18 illustrate T_i versus altitude for turbulence indicators in the 12.5 to 15.0 km region for both the Jimsphere and Wind Profile. Both wind sensors compare favorably in this high dynamic pressure region.

Summary Remarks

This research has demonstrated the results of measurements of the wind and turbulent regions from the surface to 16 km (9.94 miles) by the FPS-16 Radar/Jimsphere System and the use of these wind and turbulence assessments to validate the NASA's 50-Mhz Radar Wind Profiler. Wind Profile statistics were compared at 150-m wavelengths, a wavelength validated from 20 Jimspheres, simultaneously tracked by FPS-16 and FPQ-14 radars, and the resulting analysis of autospectra, cross-spectra, and coherence squared spectra of the wind profiles.

The standard deviation of the u and v components for STS-37 (five Jimsphere/Profiler wind profile data sets) was 1.94 m/s and 1.67 m/s, while for the STS-43 launch (six Jimsphere/Profiler wind profile data sets) the standard deviation was 1.39 m/s and 1.44 m/s, respectively. The overall standard deviation was 1.66 m/s for the u component and 1.55 m/s for the v component. It is further demonstrated that the NASA prototype wind profiler is an excellent monitoring device illustrating the measurements of the winds within one-half hour of launch zero (L-0). This fills in the time gap of wind profiles closer to L-0 during the Space Shuttle launch. The ascent wind loads are computed 2 h before launch based on winds aloft obtained by the Jimsphere.

Comparative measurements of the Jimsphere and the Wind Profiler for the vertical gradient (turbulence), Richardson number, stability parameter, scalar wind, and turbulence probability index indicate that the NASA's 50-MHz Radar Wind Profiler could play an important role in monitoring winds for substantial wind profile changes during launch procedures for the National Aerospace Plane. In addition the rapid turnaround wind measurement by NASA's 50-Mhz Radar Wind Profiler will be a tremendous boost for the speed-up schedule for NASA's Space Station Freedom program and for human space exploration of the moon and Mars in the next century.

Acknowledgments

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