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CT-140-88-9

MLS SIGNAL STRENGTH MEASUREMENTS
AND MLS MATHEMATICAL MODELING OF
RUNWAY 17R HUMP AT DENVER COLORADO,
STAPLETON AIRPORT

By Jesse D. Jones

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MAY 28 1988

FAA TECHNICAL CENTER
ATLANTIC CITY, N.J. 08405

Engineering Division
FAA Technical Center
Atlantic City International Airport, N.J. 08405

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Background

The tests described in this report resulted from discussions held at Hazeltine Corporation in Commack, New York on August 28, 1987. It was decided at this meeting that, due to differences in the output between FAA and Hazeltine math models, a joint FAA/Hazeltine project was to be undertaken to measure the actual threshold signal strength of an MLS signal transmitted over a humped runway. These measurements were then to be compared to output from both the Hazeltine Wedge and the FAA Wait/Conda math models in an attempt to reconcile the differences. It was decided to perform the measurements at runway 17R at Denver Stapleton International Airport which has a severe hump of approximately 60 feet.

At a later meeting held at the FAA Technical Center on October 5, 1987, it was decided to first perform the tests at the FAA Technical Center during the period October 19-21, 1987 to ensure that the transmitting and measurement systems, as well as the test methodology were satisfactory. Technical Center runway 04/22 was selected for the tests because a hump of approximately 7 feet (ft) exists between the threshold of runway 04 and the midpoint of the runway. The Technical Center tests were performed and are documented by an ACT-100 report CT-140-88-3 entitled "MLS Signal Strength Measurements and MLS Math Modeling of Runway 4-22 Hump at the FAA Technical Center". It was concluded that the transmitting system, measurement system, and test methodology was satisfactory for the measurements at Denver.

Objective

The primary objective of the test on Denver runway 17R was to determine the minimum Azimuth transmitter phase center height which would meet the MLS signal strength specifications at threshold. A secondary objective was to compare the runway hump shadowing effects as computed by the Wedge and Wait/Conda models with the measured signal level data.

Test Description

As shown in figure 1, the transmitter was sited at a distance of 1,170 ft from the threshold of runway 35L on the extended centerline of the runway. The mean sea level (msl) ground elevation of the transmitter site was 5,286.4 ft. The transmitter was tuned to a frequency of 5,061.00 MHz, a mid-band frequency which corresponds to MLS channel 600. A standard gain horn of 18.6 dB gain at 5,061.00 MHz was used as the transmitting antenna (figure 2). For some measurements, an MLS differential phase shift keying (DPSK) ident function antenna was used as the transmitting antenna to more closely approximate the signal characteristics of an actual MLS antenna. The effective radiated power output of the transmitting system was calibrated prior to the start of each of the tests.

The receiving and measurement system (figure 3) was installed in a mobile test van equipped with a vertical antenna mast which allowed the receiving antenna to be raised to a height of 50 ft above ground level (agl). The test van was positioned so that the receiving antenna was located over test points on the runway centerline at ranges of 6,094 and 11,500 ft (7,264 and 12,670 ft from transmitter) from the runway stop end. The receiving antenna was mounted on a variable height mast and positioned 8 ft agl at the lower limit of the mast height. As the mast was raised, the antenna would reach the upper limit of 48

2000

2000

feet. A typical set of measurements consisted of setting the receiving antenna 8 ft agl, activating the measurement system, and continuously recording the signal strength as the receiving antenna was smoothly raised to about 45 ft agl. At this height, the measurement system was deactivated and the receiving antenna repositioned to 48 ft agl. Then the measurement system was reactivated and the signal strength recorded as the antenna was smoothly lowered to 8 ft agl. This sequence was repeated to record a minimum of two sets of ascending and two sets of descending measurements for each phase center height. This test scenario was performed at two measurement locations (6,094 and 11,500 ft from runway stop end) and 3 phase center heights (5,293, 5,295.2, and 5,297.9 ft msl). The measurements presented in this report were recorded during the second night (December 9, 1987). Measurements recorded during the first night are not included in this report because they were affected by high winds, and therefore, judged of inferior quality.

Computation of MLS Mathematical Model Input Parameters

1. General

Plan and Profile drawings for runway 17R/35L were obtained from the airport engineering office. These were as-built drawings for an overlay project which had raised the runway surface to its current height. To be useful for modeling purposes, distance/elevation data pairs are required along the runway centerline. Therefore, the runway centerline profile was digitized from the drawings at increments of approximately 50 ft and stored in two data files (one for distance and one for elevation). These data files were then used as the source for the runway centerline profile plot (figure 1) and the "least squares best fit" computations for determining one of the cylinder radii used in the Wait/Conda model (177,395 ft). Cylinder radii which were determined graphically (197,050 and 273,220 ft) by the use of a software package called MathCAD used the runway centerline profile from the Denver Obstruction Chart. These radii, however, are shown later in this report with respect to the digitized, or actual, runway profile.

The Wedge model that was used for modeling the hump on runway 04/22 at the Technical Center could not accommodate the runway profile configuration at Denver, so the secondary objective, to compare the Wedge and Wait/Conda models with measured data, was not achieved. Mr. A. Lopez of Hazeltine developed a methodology for computing power density for a runway with a complex profile (multiple humps, including an inverted hump) and used it to model the same runway at Denver. Since the new methodology was not made available to the FAA, a comparison between the Wedge and Wait/Conda models for modeling humped runways is not presented in this report.

2. Computation of Wait/Conda model input data

This report includes model output plots for three different cylinder radii. The first two radii were derived from earlier modeling for Denver which was reported in a letter to APS-410 dated September 16, 1987 and titled "Mathematical Modeling of the Runway Hump on Denver Runway 17R". In that letter modeling results at threshold were provided for 2 phase center heights: 5,294.12 and 5,295.12 ft msl. In that letter it was stated that for phase center heights below 5,295 ft msl, the hump should be simulated by a cylinder located at the stop end of the runway with a radius of 197,050 feet since the runway surface was shadowed by the stop

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end. Above 5,295 ft, the letter stated that the cylinder should be located about 875 feet down the runway from the stop end with a radius of 273,220 feet since the runway surface would now be illuminated and be a factor in the shadowing effects. Both of these radii were remodeled for the three phase center heights corresponding to the actual field measurements.

The third radius modeled for this report was derived by applying a "least squares best fit" to the runway curvature from 1,499.4 to 2,991.5 feet from the stop end of the runway. This section of runway was chosen since it is the part of the runway which smoothly transitions from the relatively level surface near the stop end of the runway to the steep slope of the runway midsection. The radius which best fit this curvature was determined to be 177,395 feet with the peak located 1,461 ft from the runway stop end.

Since the Wait/Conda model requires as input, a coordinate pair for the peak of the cylinder and two additional coordinate pairs equally spaced on either side of the peak, the radii chosen required conversion into these three coordinate pairs. In the Wait/Conda model, the radius of the cylinder is computed as:

$$r = (h^2 + d^2)/2h$$

The variables referenced in the above equation are depicted graphically on figure 4. Since r is known, we assumed a value of 2,000 (+/- 1,000) for d and solved for h . This provides two coordinate pairs 1,000 feet on either side of the peak coordinate pair. These three coordinate pairs were then used as the input to the Wait/Conda model as the specification for the runway hump.

Signal Level Conversions

The Wait/Conda model output represents the signal level in the presence of shadowing effects compared to the direct (free space) signal in the absence of any shadowing effects. Therefore to convert the model output data to dBm for comparison purposes, the effective radiated power, less the propagation loss, was subtracted from the model output. The requirement for the MLS signal coverage is -89.5 dBw/m² at 8 ft above the runway surface. To convert this value to dBm, a value of 5.5 is subtracted yielding a required dBm level of -95. This is the signal level at the origin of the y-axis on the plots shown in this report.

Data Presentation and Analysis

The comparative signal level plots presented in this report show the Wait/Conda model output as a solid line. The measured data is presented as dots with a solid line marking the average measurement values. The measured data presented generally consists of four sets of data, two from 48 to 8 ft, and two from 8 to about 45 (42-45) ft. The x-axis of the signal level plots indicates the measurement (and modeled) height above ground in feet. The y-axis of the plots shows the measured (and modeled) signal level in dBm. Only measured data using a horn antenna was processed for presentation in this report.

Figure 5 shows the relationship of the cylindrical hump to the runway profile for a radius of 197,050 feet (determined graphically) with a peak at the stop end of the runway. This is the same cylinder used for previous modeling of Denver for phase centers below 5,295 feet msl. The results of modeling this radius with a phase center height of 5,293 ft msl at measurement locations of 6,094 and 11,500

ft from the runway stop end are presented in figures 6 and 7, respectively. Figure 6 shows that the modeled data is within 3 dB of the average measured data above 15 ft. Above 22 ft the slopes of the two curves are similar, however, below 22 ft the slope of the modeled curve flattens, crosses the measured curve, and then diverges from it. The flattening of the curve for the modeled data, although in disagreement with the measurements at 6,094 ft, is typical of the measurements taken at 11,500 ft (threshold) from the runway stop end. This flattening, and minimums on subsequent plots are considered representative of signal in space characteristics, although misplaced (not correctly matched) by the model. Figure 7 (runway threshold with transmitter phase center of 5,293 ft msl) shows that the general contour of the modeled data follows the contour of the measured data within 5 dB, but with a bias of about 4 dB.

A phase center height of 5,295.2 ft msl was the next height modeled using the radius of 197,050 ft. Comparison plots at this phase center height are provided for the measurement locations of 6,094 and 11,500 ft from the runway stop end in figures 8 and 9, respectively. The contours of the modeled and average measured data of figure 8 are similar, but they have a divergent offset at low heights which reaches a maximum difference of 5 dB. Figure 9 shows a maximum difference of 4 dB between the measured and modeled data; however, the contour of the modeled data does not follow the flattening of the measured data contour below 25 ft.

A phase center height of 5,297.9 ft msl was also modeled, using a radius of 197,050 ft, notwithstanding our previous statement (September 16, 1987 letter) not to use this radius for phase center heights above 5,295 ft msl. This was done to gain additional insight into whether the peak at the runway end is the predominant factor in the shadowing, since measurements are now available for comparison. Comparison plots for measurements at 6,094 ft and 11,500 ft from the runway stop end are presented in figures 10 and 11, respectively. The modeled data of figure 10 generally follows the contour of the average measured data, but diverges at lower heights to a maximum difference of 8 dB. The modeled data shown on figure 11 falls within 2 dB of the average measured data; however, the contour of the modeled data does not follow the measured data contour between the heights of 20 to 38 ft above ground. Results of modeled to measured data for a circle radius of 197,050 ft. (figures 6-11) are summarized in table 1 under the column headed "Radius = 197,050."

In the previous modeling for Denver reported in our September 16, 1987 letter, it was stated that a radius of 273,220 with a peak located 875 feet from the runway stop end should be used for phase center heights above 5,295 ft msl. The profile for this cylinder is shown with the runway profile in figure 12. Again notwithstanding our previous statement, the phase center height of 5,293 ft was modeled using this radius of 273,220 ft. These results are presented by figures 13 and 14 for measurement locations of 6,094 and 11,500 ft, respectively. Figure 13 shows the contour of the modeled data to be similar to the average measured data contour, but with a slightly less positive slope, above 30 ft with a maximum difference of less than 2 dB. However, below 30 ft the curves diverge until at 15 ft the modeled curve reaches a minimum, then reverses direction, crosses, and diverges from the measured data. Above 27 ft, the contour of the modeled curve shown in figure 14 generally follows the average measurements, although with a 3 dB bias. Below this height the measurements flatten out, but the model data continues to decrease.

The data for measurements taken at a phase center height of 5,295.2 ft msl with a radius of 273,220 ft are presented in figures 15 and 16, respectively. The plot for the 6,094 ft measurement (figure 15) shows the modeled data to be within 3 dB of the average measured data. Down to a height of 27 ft above ground the contours of the two curves are similar. The curves then diverge down to a height of 9 ft where the modeled data curve reverses direction. The modeled data also has a slightly more positive slope than the measured data above the reversal point. The modeled data contour shown on figure 16 does not follow the 11,500 ft measured data contour below 25 ft, but is within 2 dB of the average measured data above 25 ft.

The results of modeling a phase center height of 5,297.9 ft msl with a radius of 273,220 ft at measurement locations of 6,094 and 11,500 ft are presented in figures 17 and 18, respectively. Although the modeled data of figure 17 has a more positive slope than the average measurements, the differences are within 3 dB. The modeled data of figure 18 falls within 2 dB of the average measured data above 25 ft; however, below 25 ft, the modeled data contour diverges from the measured data reaching a maximum difference of 6 dB at the lowest measured height. Results of modeled-to-measured data for a circle radius of 273,220 ft (figures 13-18) are summarized in table 1 under the column headed "Radius = 273,220."

Figure 19 is the cylinder profile for a radius of 177,395 ft. This radius was determined by a "least squares best fit" method to match the curvature of the runway surface between 1,492 ft and 2,992 ft (1,499.411 and 2,991.549 ft were the closest digitized points, and therefore, the actual range of values used) from the stop end. These distances were determined from the runway profile drawings as the locations which the runway curvature (the linear sections of the runway on either side are tangential to the curved section) began and ended for the portion of the runway expected to produce diffraction effects. A phase center height of 5,293 ft was modeled with this radius for measurement locations of 6,094 and 11,500 ft. These results are presented in figures 20 and 21, respectively. The modeled data of figure 20 does not provide a good representation of the average measured data, although the levels are within 5 dB. The model output shown in figure 21 falls within 3 dB of the average measurements; however, between 15 to 25 ft, the contour of the modeled curve does not match the measured data contour. On either side of this region the measured data is on the opposite side of the modeled data.

A phase center height of 5,295.2 ft is above the elevation of the runway stop end and considered more appropriate for the radius of 177,395 ft. The results of simulations at this phase center height for measurement locations of 6,094 and 11,500 ft are presented in figures 22 and 23, respectively. Figure 22 shows that the contour of the modeled data is similar to the average measurement contour, but has a more positive slope. The maximum difference is about 5 dB at 45 ft above ground. The maximum difference between modeled and measured data shown on figure 23 is less than 3 dB; however, the modeled data continues to decrease in amplitude below 25 ft while the measured data begins to level out. The plots of figures 24 and 25 show the results of modeling a phase center height of 5,297.9 ft with the cylinder radius of 177,395 ft at measurement locations of 6,094 and 11,500 ft, respectively. Figure 24 shows similar curves, although slightly different slopes, between the modeled and measured data. The maximum difference depicted on figure 24 is about 3 dB. The modeled data shown in figure 25 is within 1 dB of the average measured data above 25 ft, but diverges from the

measured data to a 4 dB difference at the lowest measurement height. Results of modeled to measured data for these three radii at the two measurement locations are summarized in table 1.

To determine the required phase center height for the Denver MLS installation requires consideration of the total runway surface, particularly the region which is shadowed. In addition, the measurements presented were obtained using only a horn antenna. In the actual MLS installation, the signal level requirements will have to be met with a DPSK antenna. Therefore, modeling of a DPSK antenna was also performed for a flightpath 8 ft above the runway surface and extending from threshold to 2,992 ft from the runway stop end, a point at which line of sight should exist. This modeling was performed using the 177,395 ft radius which had the best agreement at the 8 ft height between the modeled and measured data.

When modeling the DPSK antenna, additional correction factors must be applied to account for the rolloff of the antenna gain at the horizon. A vertical radiation pattern for a typical DPSK antenna would show a gain of about 14.1 dBi at the peak and about 8.3 dBi (5.8 dB below the peak) at the horizon. Therefore to simulate a DPSK antenna, the model output data would be corrected for the slope (assumed linear) of the antenna as a function of the vertical angle as follows:

$$\text{corrected value} = \text{raw data} + 8 * \text{angle} - 5.8$$

where:

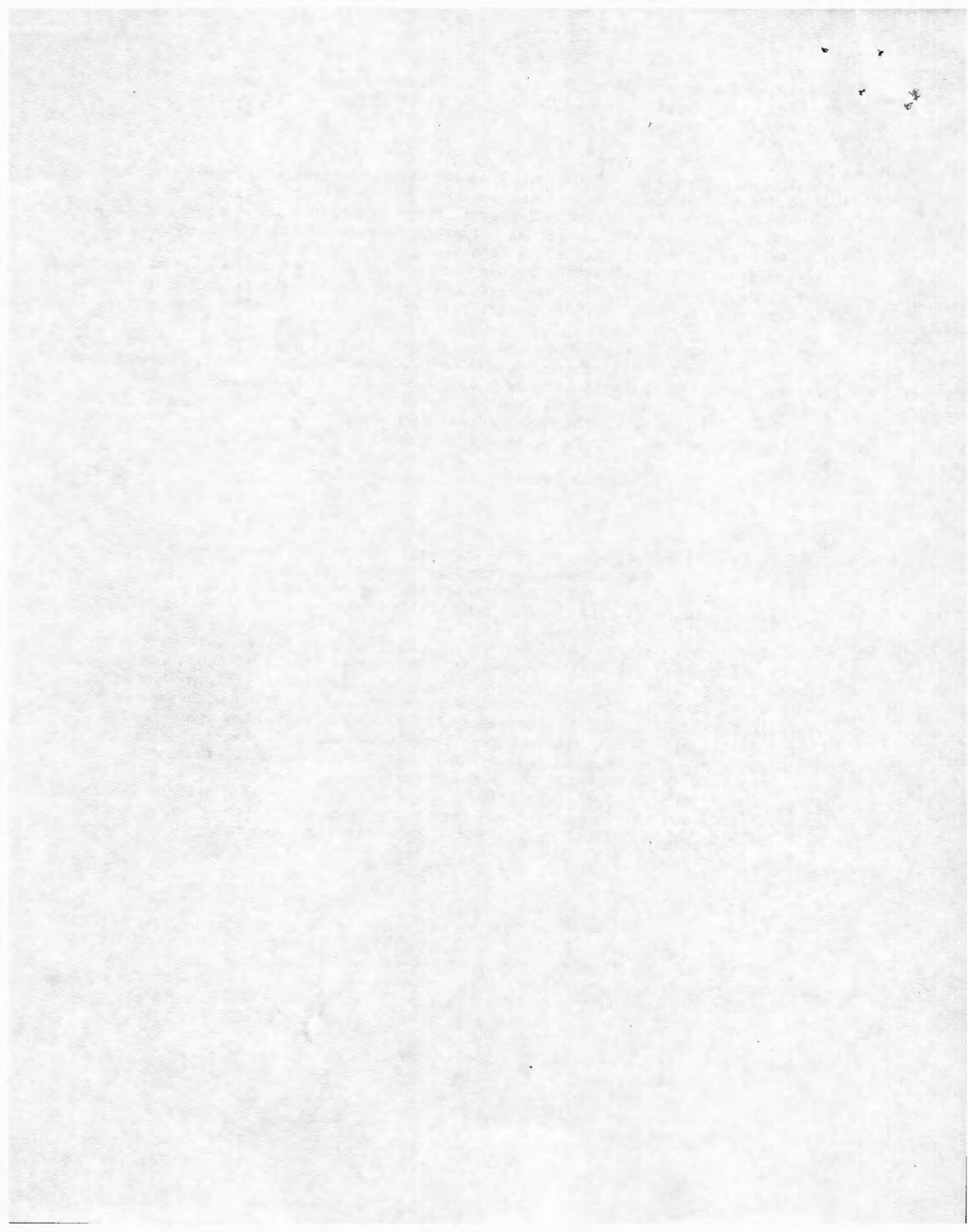
8 = slope (dB/deg) of DPSK vertical antenna pattern near the horizon
angle = elevation angle (deg) between the transmitting
antenna phase center and the measurement point
5.8 = vertical pattern loss (dB) of DPSK antenna at the horizon

Initially, a horn antenna was used for modeling an 8 ft flight path with a phase center height of 5,295.2 ft (figure 26). The signal levels at 6,094 and 11,500 ft (in figure 26) may be compared with the signal levels at 8 ft on figures 22 and 23, respectively. A DPSK antenna was subsequently modeled with the results shown in figure 27. This figure shows that a DPSK antenna at a phase center height of 5,295.2 ft msl will not meet the minimum signal requirements in the vicinity of 6,100 ft from the runway stop end. This same simulation at 8 ft above the runway was repeated for a phase center height of 5,297.9 ft msl (about 12 ft above ground). The results for a horn antenna and a DPSK antenna are shown in figures 28 and 29, respectively. Figure 29 shows that a phase center height of 5,297.9 ft msl will just meet the minimum signal requirements over the total region of shadowing.

Conclusions

The best overall match between modeled and measured data for the 5,293 ft phase center height occurred with a radius of 273,220 ft (figure 13) for a measurement location of 6,094 ft from the runway stop end. At the 11,500 ft measurement location, the best match in level occurred with the 177,395 ft (figure 21) radius. However, the best match for shape occurred with the 197,050 ft (figure 7) radius.

At the 5,297.2 ft phase center height the best match for shape between modeled and measured data occurred with the 197,050 ft (figure 8) radius at the 6,094 ft



* measurement location. At the 11,500 ft location, no model output provided a shape matching the measurements; however, the 177,395 ft (figure 23) radius provided the best match in level.

The radius of 273,220 ft (figure 17) appears to be the best overall match for a phase center height of 5,297.9 at the 6,094 ft measurement location; however, all of the modeled data for this phase center height had a slope more positive than the measurements. At the 11,500 ft measurement location, the radius of 197,050 ft (figure 11) provided the best match for level, although none of the radii were able to provide a good match to the shape of the curve.

In consideration of the above results, no clear correspondence is evident to support a single radius for all phase center heights at all measurement locations. Neither, is there any evidence to support any pattern to the correspondence between the data and measurements. However, the modeled data appears to correspond better with the measurements at Denver than was evident with the comparison for the runway 4 measurements at the FAA Technical Center.

A phase center height of approximately 5,298 ft (12 ft agl) is required to meet the minimum MLS signal requirements at 8 ft agl when the total region of shadowing along the runway is considered.

Wedge model data is not presented in this report because the new version that could model multiple and inverse runway humps was not made available to the FAA.

Recommendations

In the documentation for the Wait/Conda model and the methods of application to runway hump modeling in the MLS model, it is stated that some of the constants used in the model are derived from measurements at Bedford, England. With this in mind it appears that with the availability of the Denver and FAA Technical Center measurements, further study should be performed to determine if these constants need to be revised. First, however, more knowledge must be acquired in order to correctly define the runway hump parameters for the Wait/Conda model. Time and manpower constraints prevented any action related to the above recommendations.

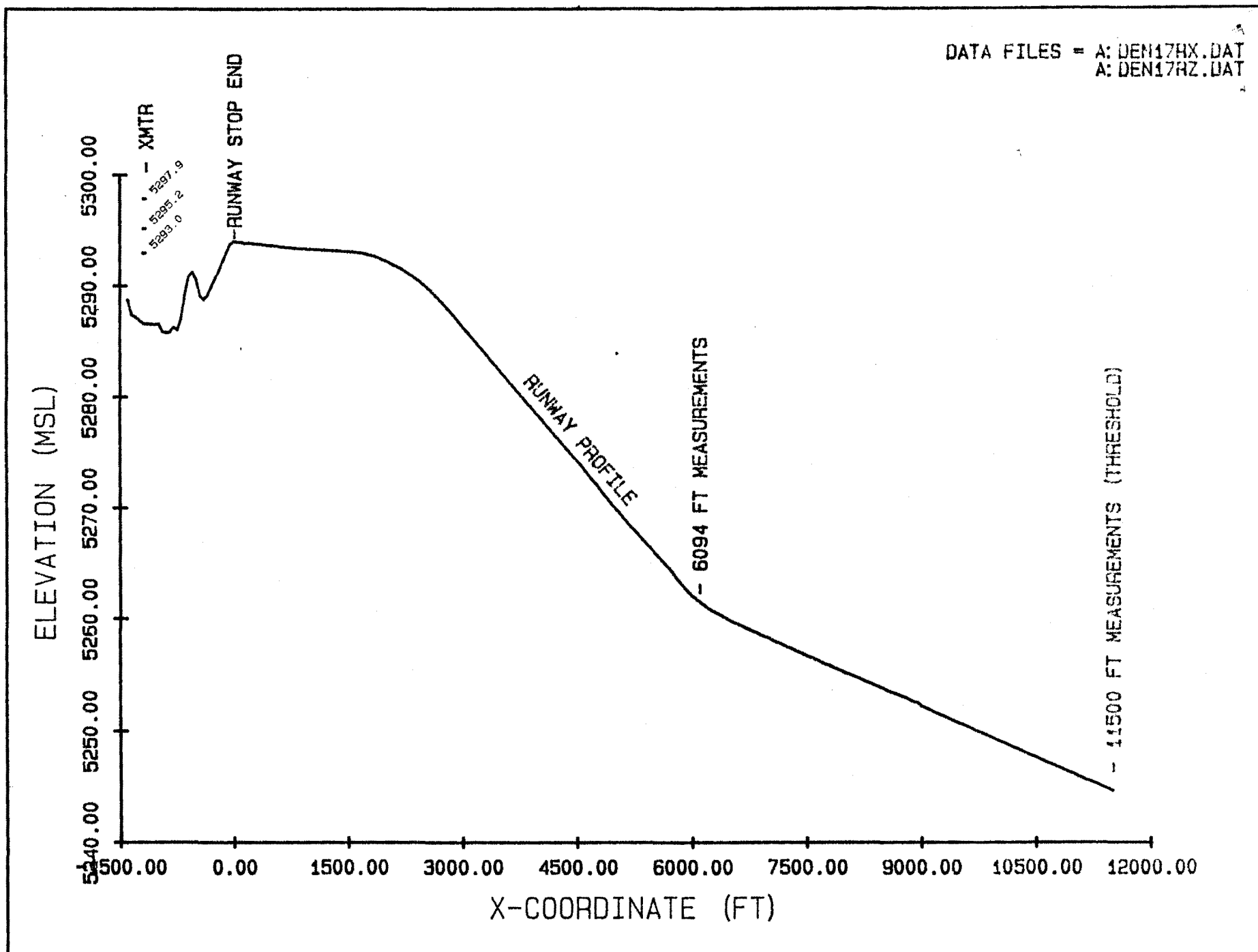
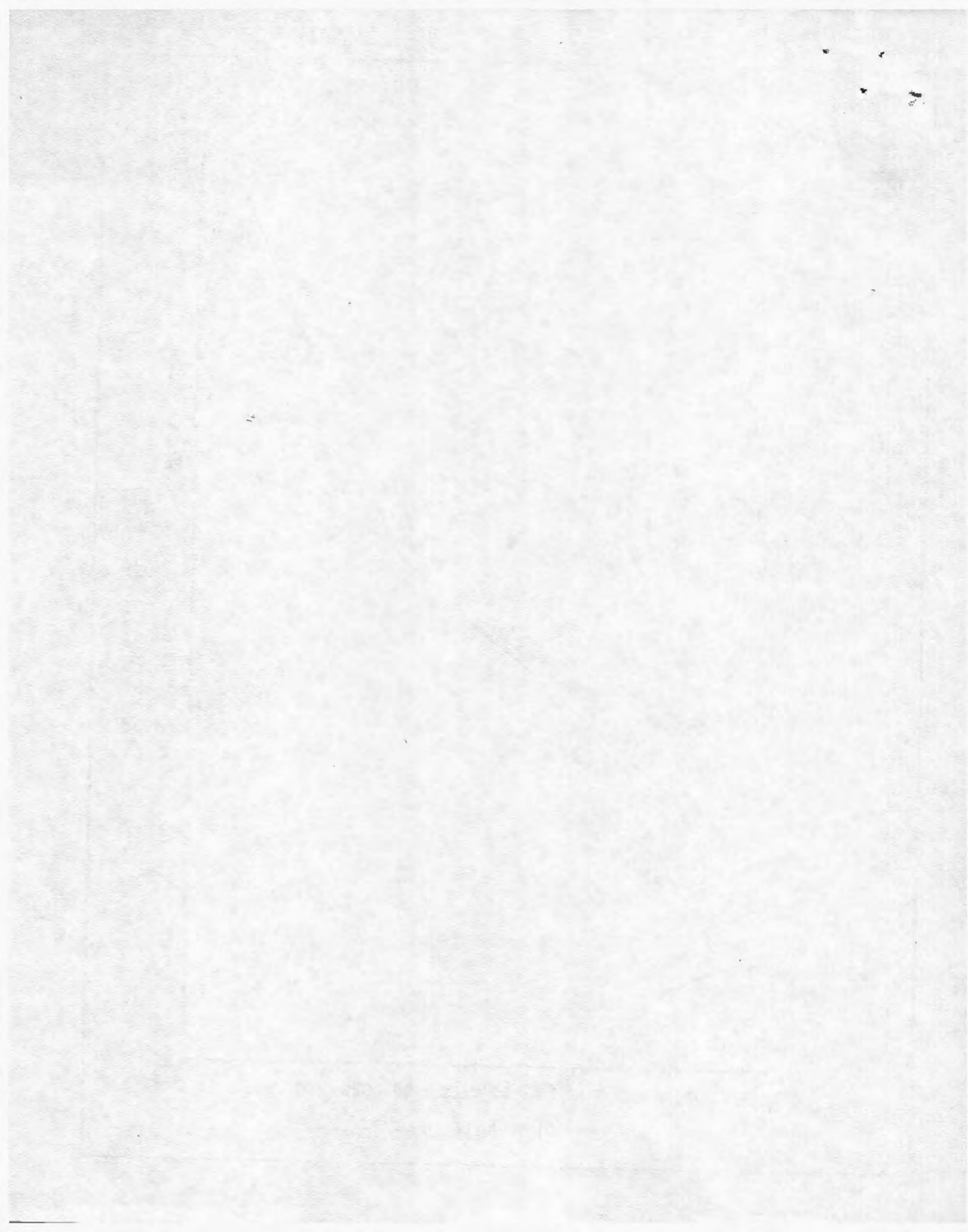


FIGURE 1. DENVER RUNWAY 17R/35L CENTERLINE TERRAIN PROFILE.



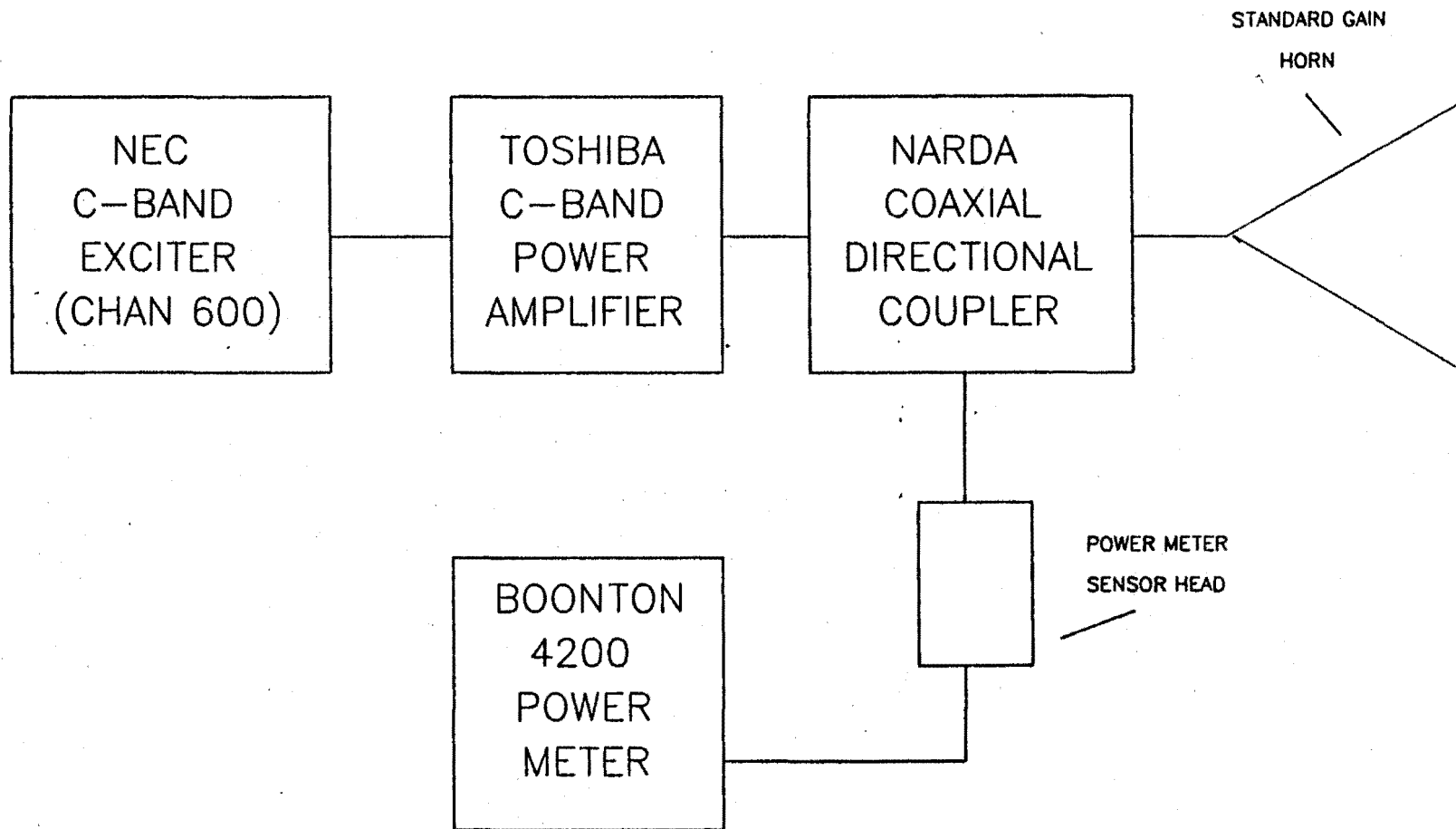
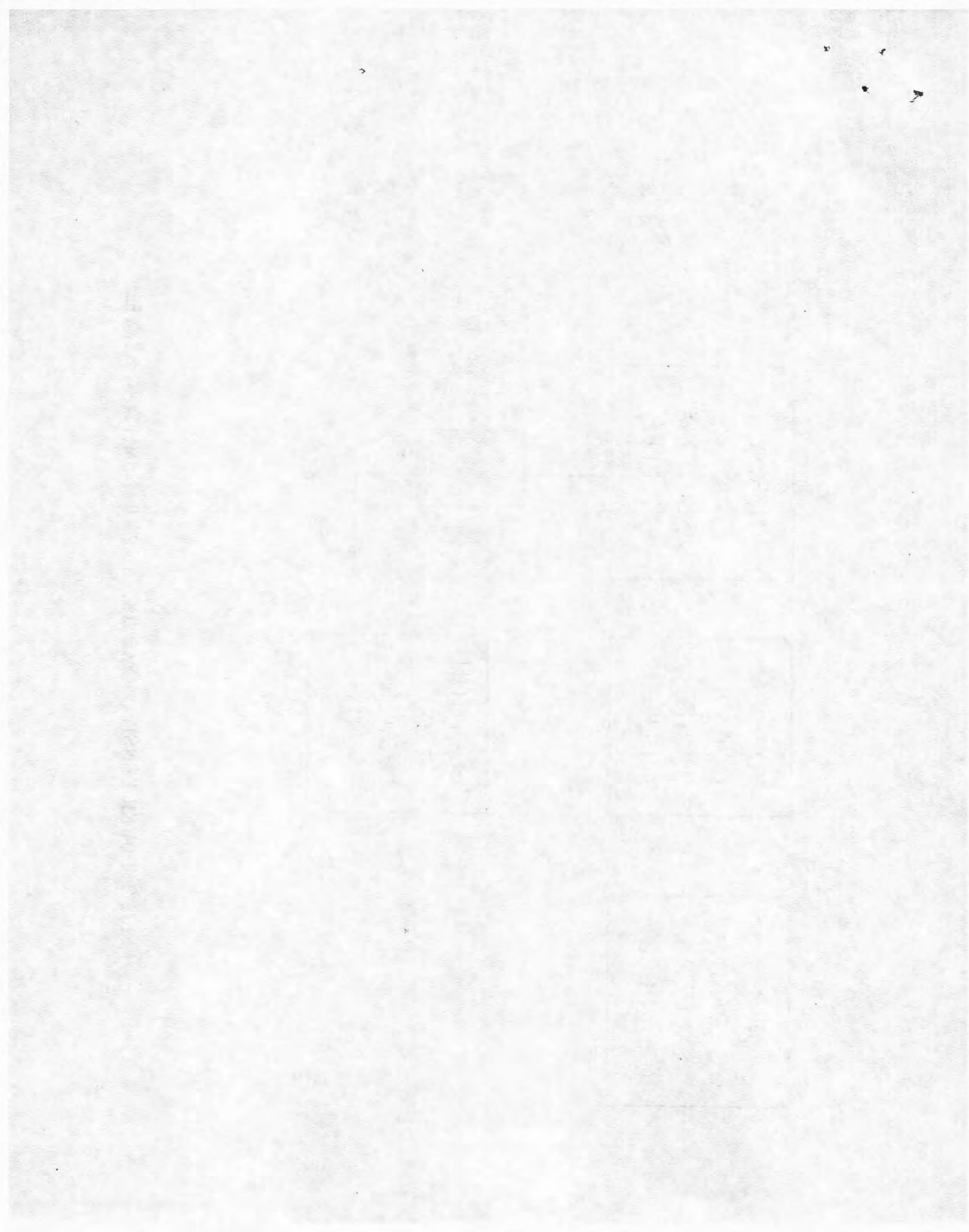


FIG. 2 POWER DENSITY MEASUREMENT TRANSMITTING SYSTEM



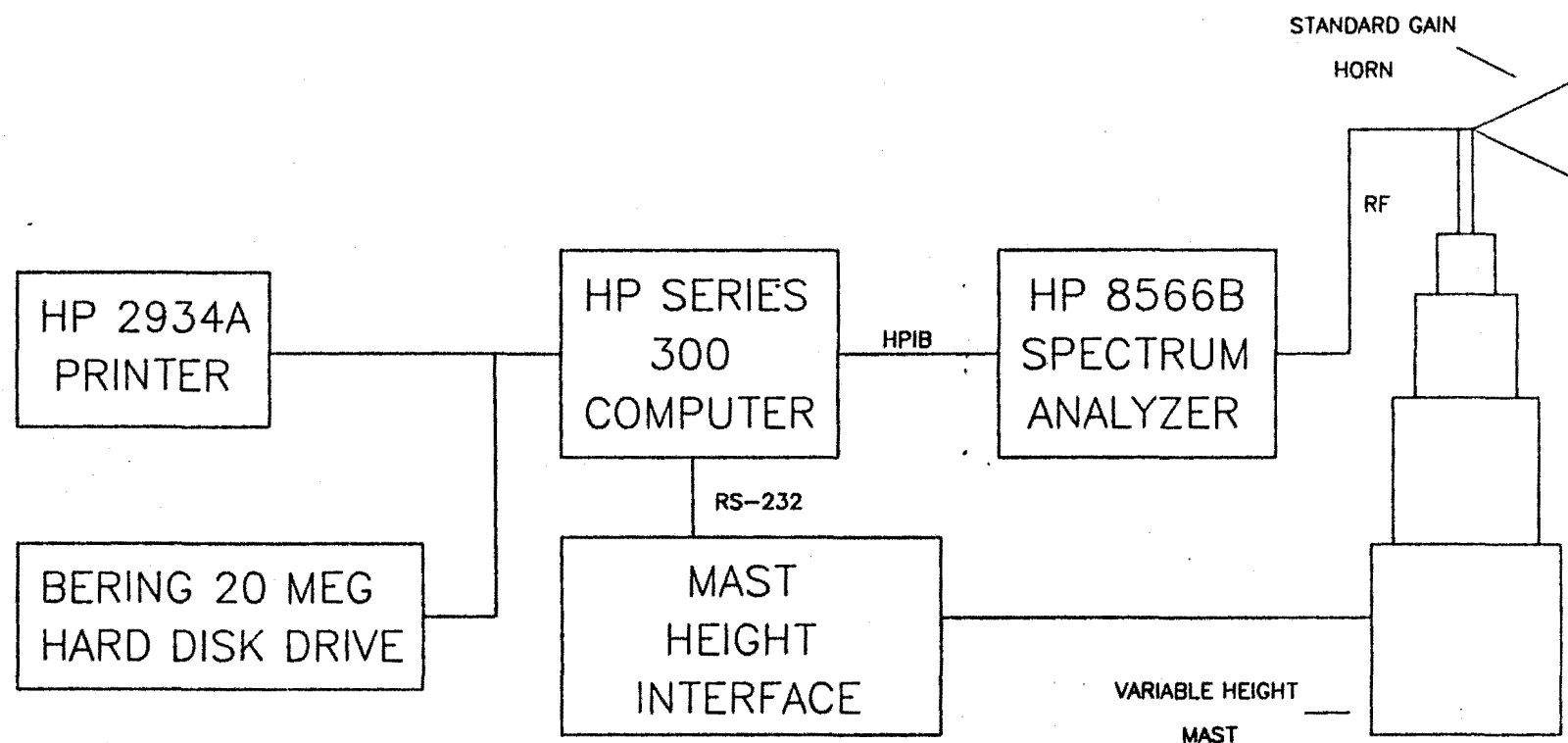
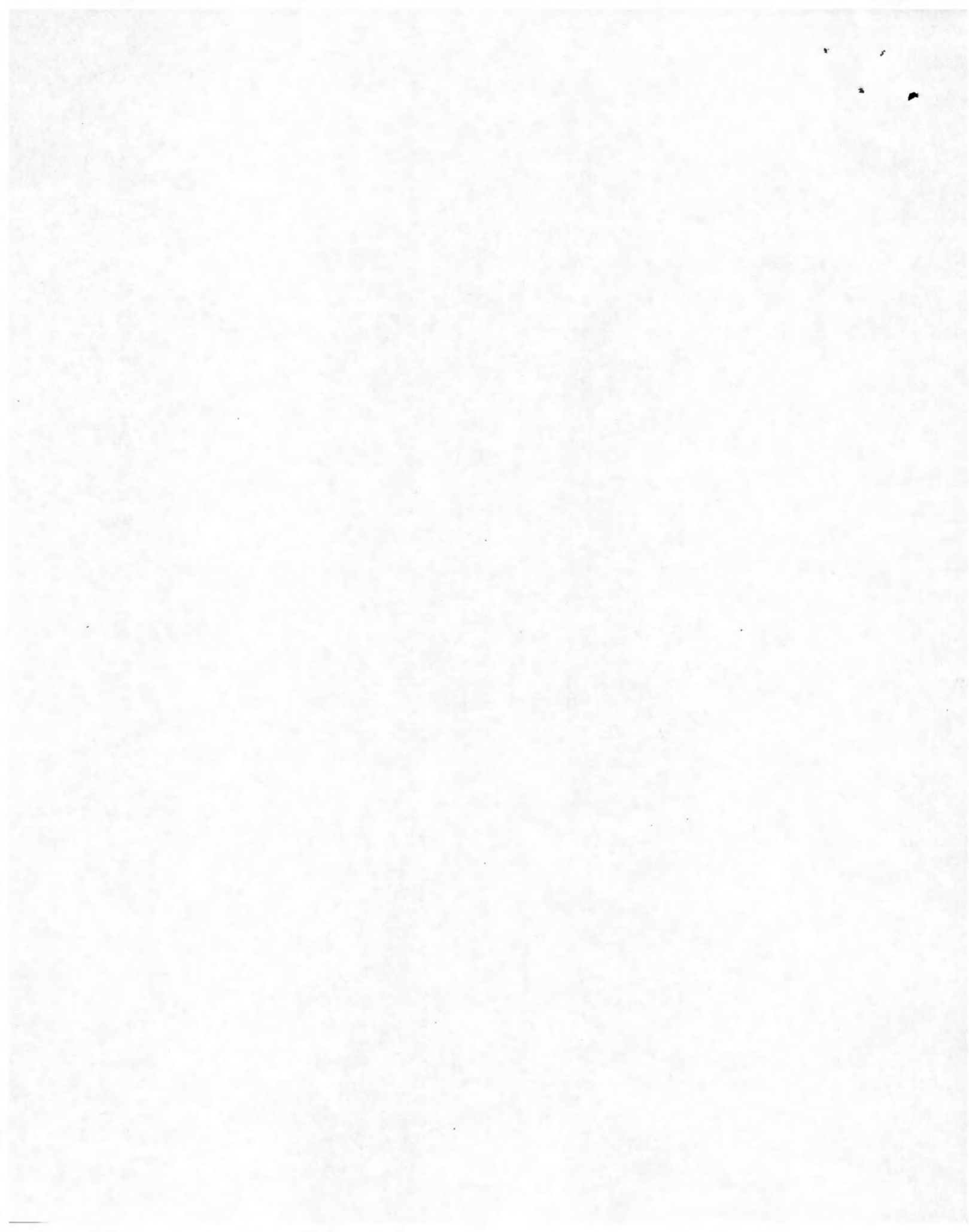


FIG. 3 POWER DENSITY MEASUREMENT RECEIVING SYSTEM



SHADOWING BY RUNWAY HUMP

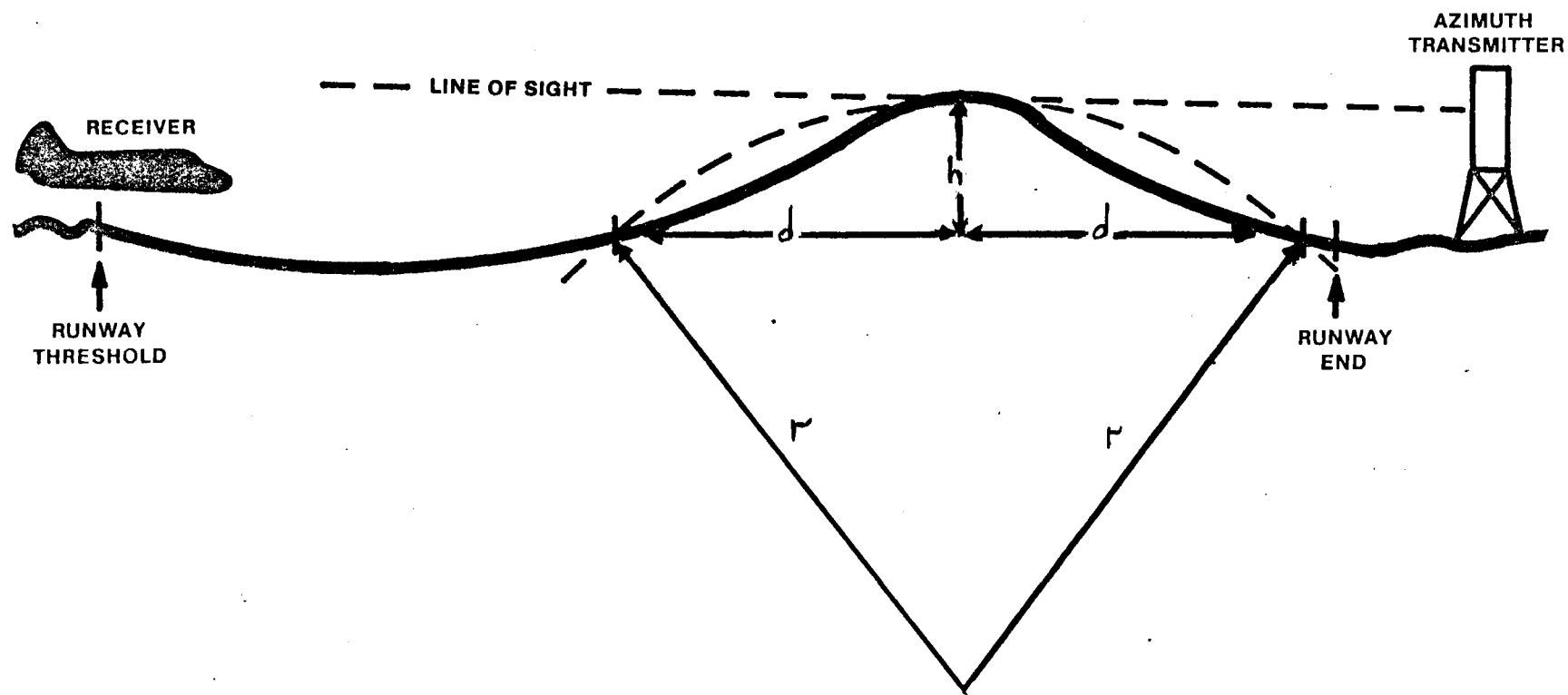


Figure 4. Definition of Wait/Conda Model Cylinder Radius

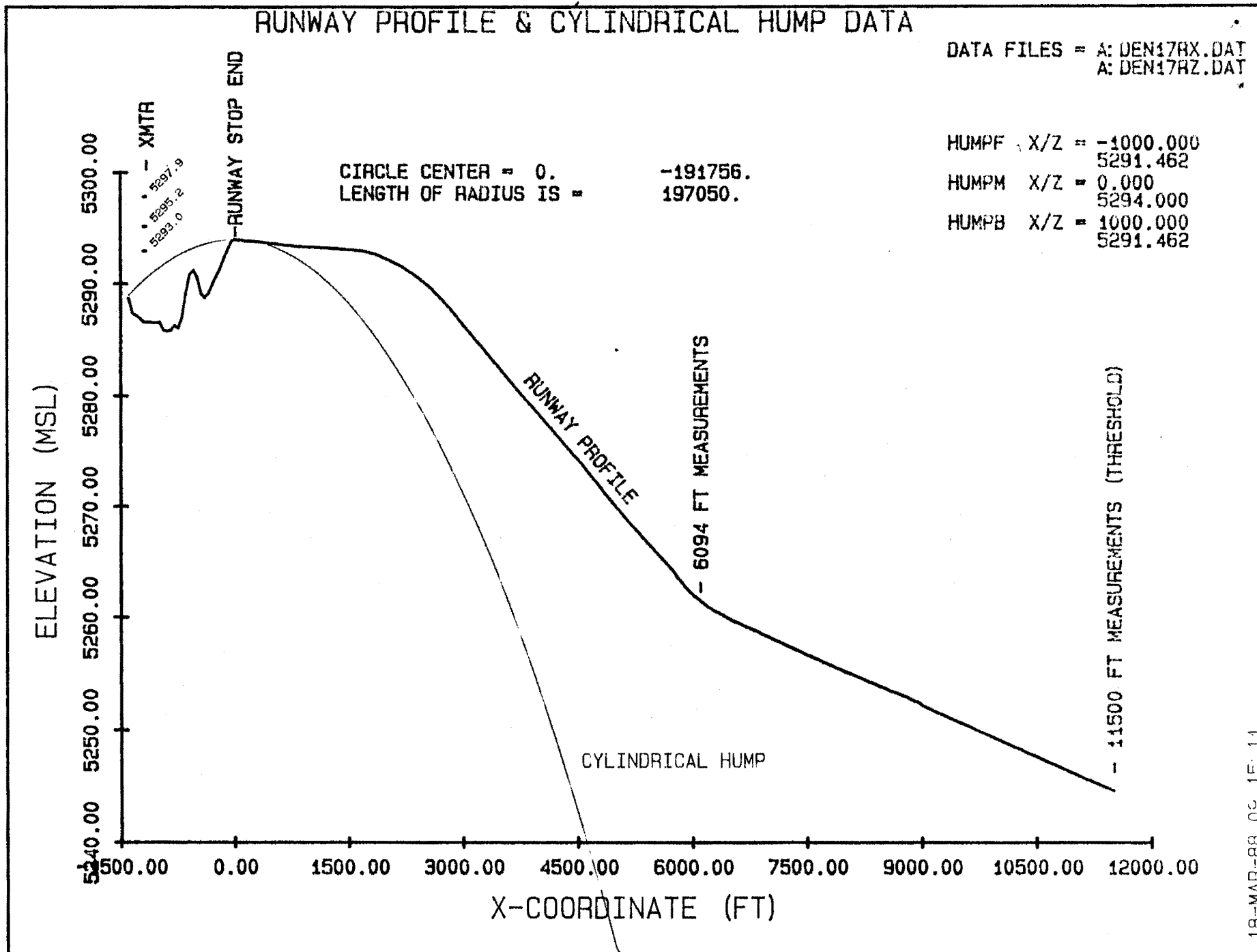


FIGURE 5. CYLINDRICAL HUMP PROFILE FOR RADIUS = 197050 FEET.

MLS MATHEMATICAL MODELING PERFORMED BY:
FAA TECHNICAL CENTER, ACT-140
ATLANTIC CITY AIRPORT, NJ 08405
TITLE: RCVR = 6094 FT, XMTR = 5.6 FT AM, RADIUS = 197050
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RUNWAY: 17R AIRPORT: DENVER, COLORADO (STAPLETON)

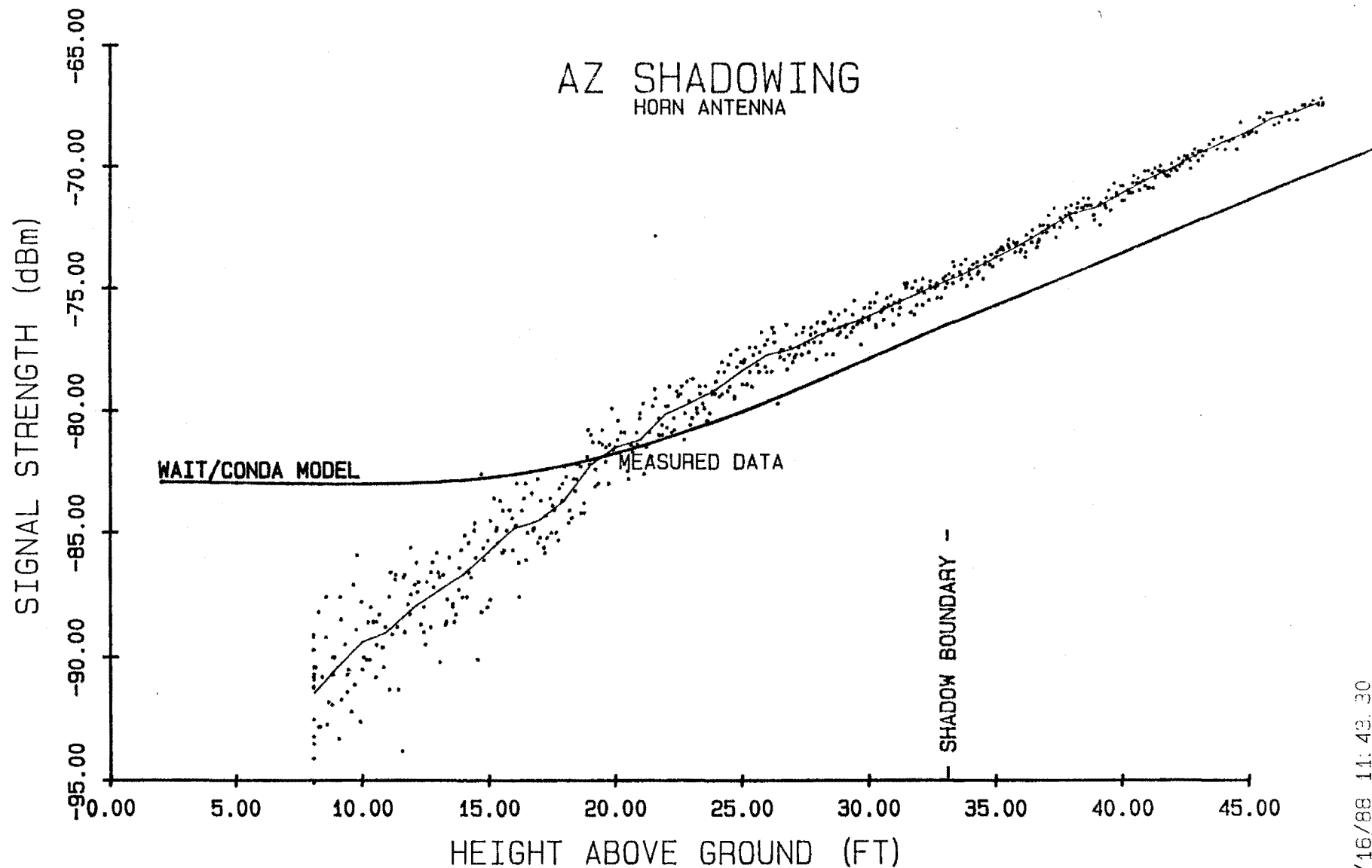


FIGURE 6. COMPARATIVE SIGNAL STRENGTH DATA FOR 6094 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5293.0 FEET MSL.

03/16/88 11:43:30

MLS MATHEMATICAL MODELING PERFORMED BY:
FAA TECHNICAL CENTER, ACT-140
ATLANTIC CITY AIRPORT, NJ 08405
TITLE: RCVR = 11500, XMTR = 5.6 FT AM, RADIUS = 197050
RUN #: 5293 DATE: 16-MAR-88 11:16:16
RUNWAY: 17R AIRPORT: DENVER, COLORADO (STAPLETON)

AZ SHADOWING HORN ANTENNA

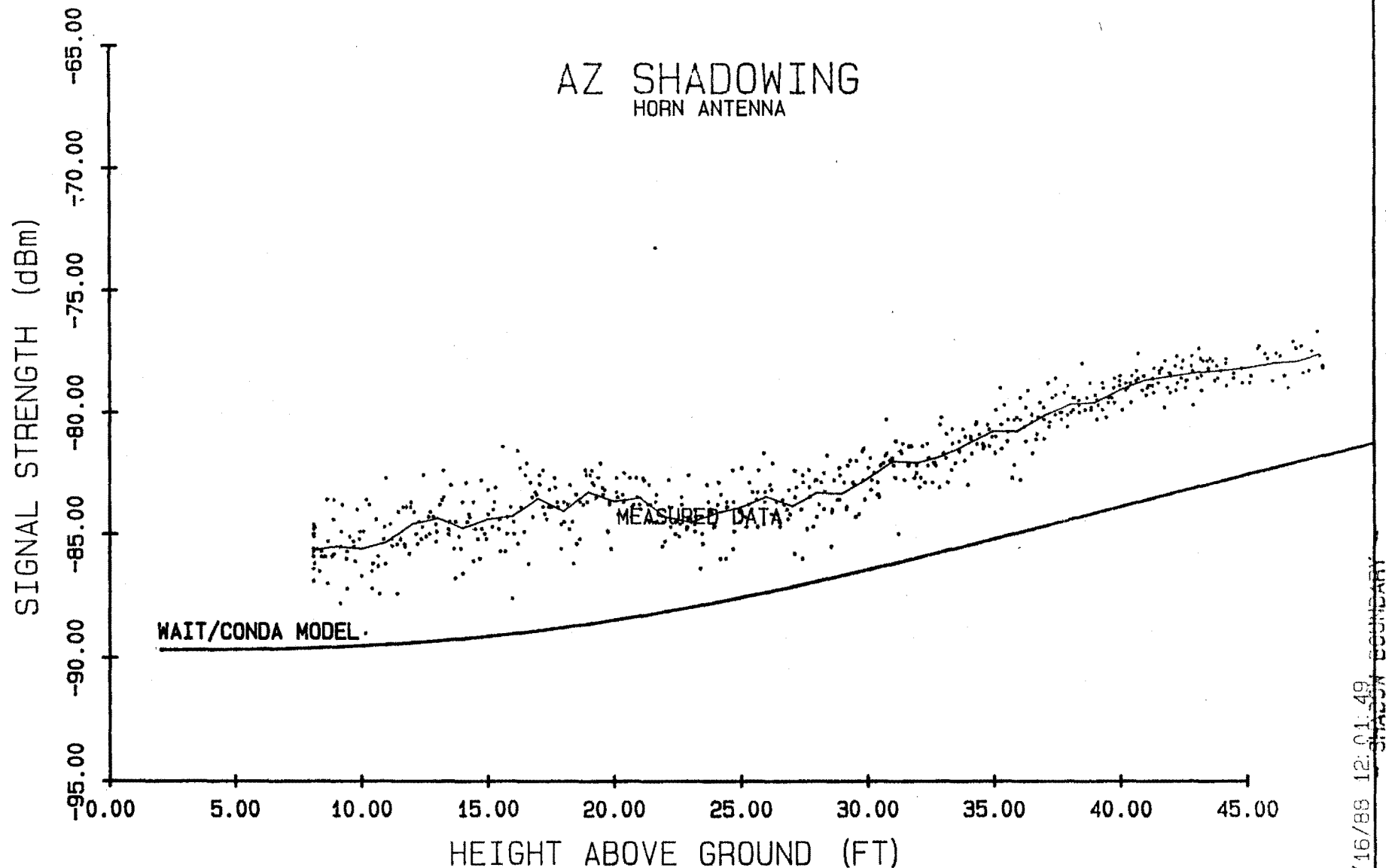


FIGURE 7. COMPARATIVE SIGNAL STRENGTH DATA FOR 11500 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5293.0 FEET MSL.

03/16/88 12:01:49
SHADOW BOUNDARY

MLS MATHEMATICAL MODELING PERFORMED BY:
FAA TECHNICAL CENTER, ACT-140
ATLANTIC CITY AIRPORT, NJ 08405
TITLE: RCVR = 6094 FT, XMTR = 7.8 FT AM, RADIUS = 197050
RUN #: 5295 DATE: 16-MAR-88 11:13:44
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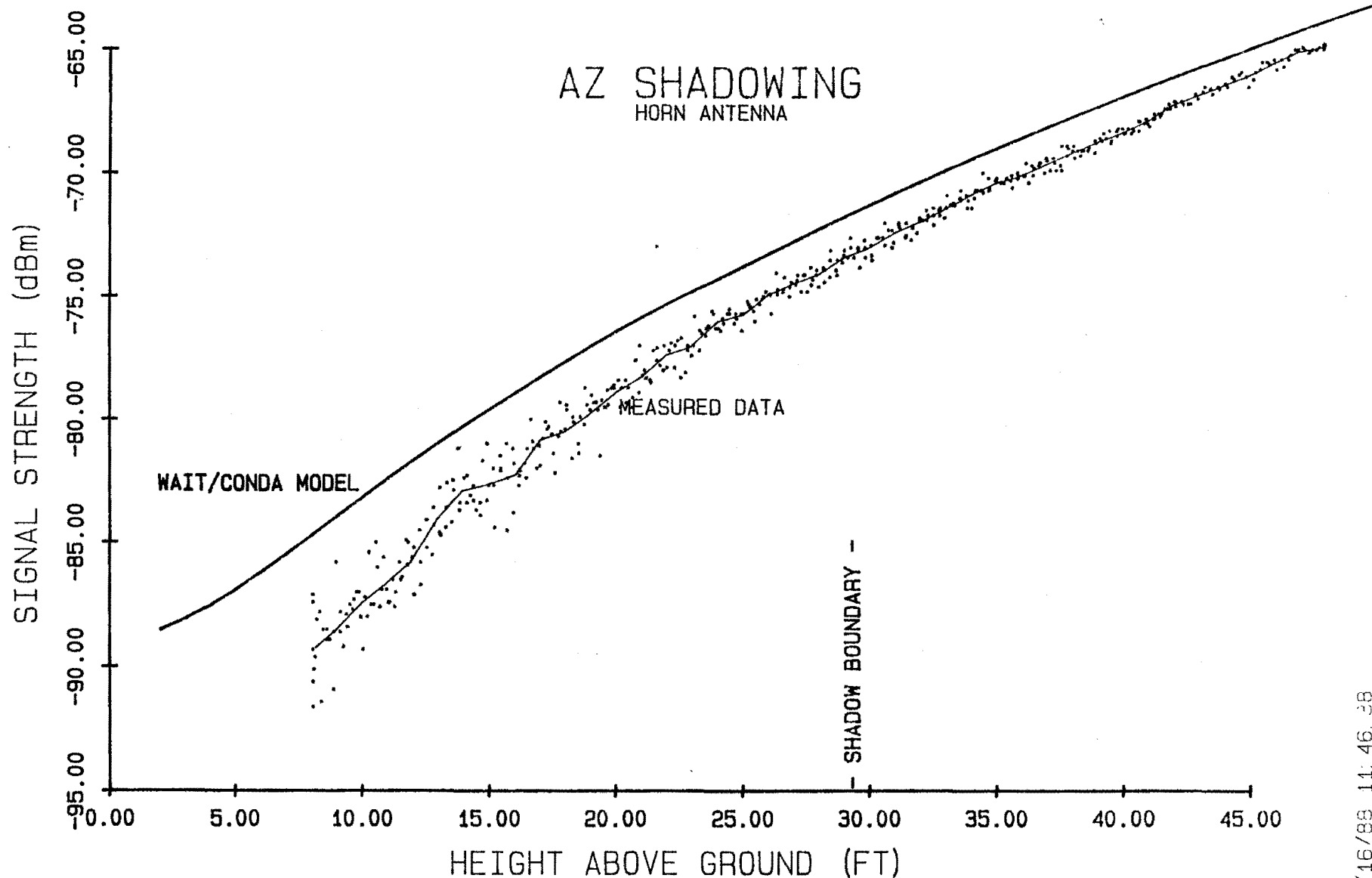
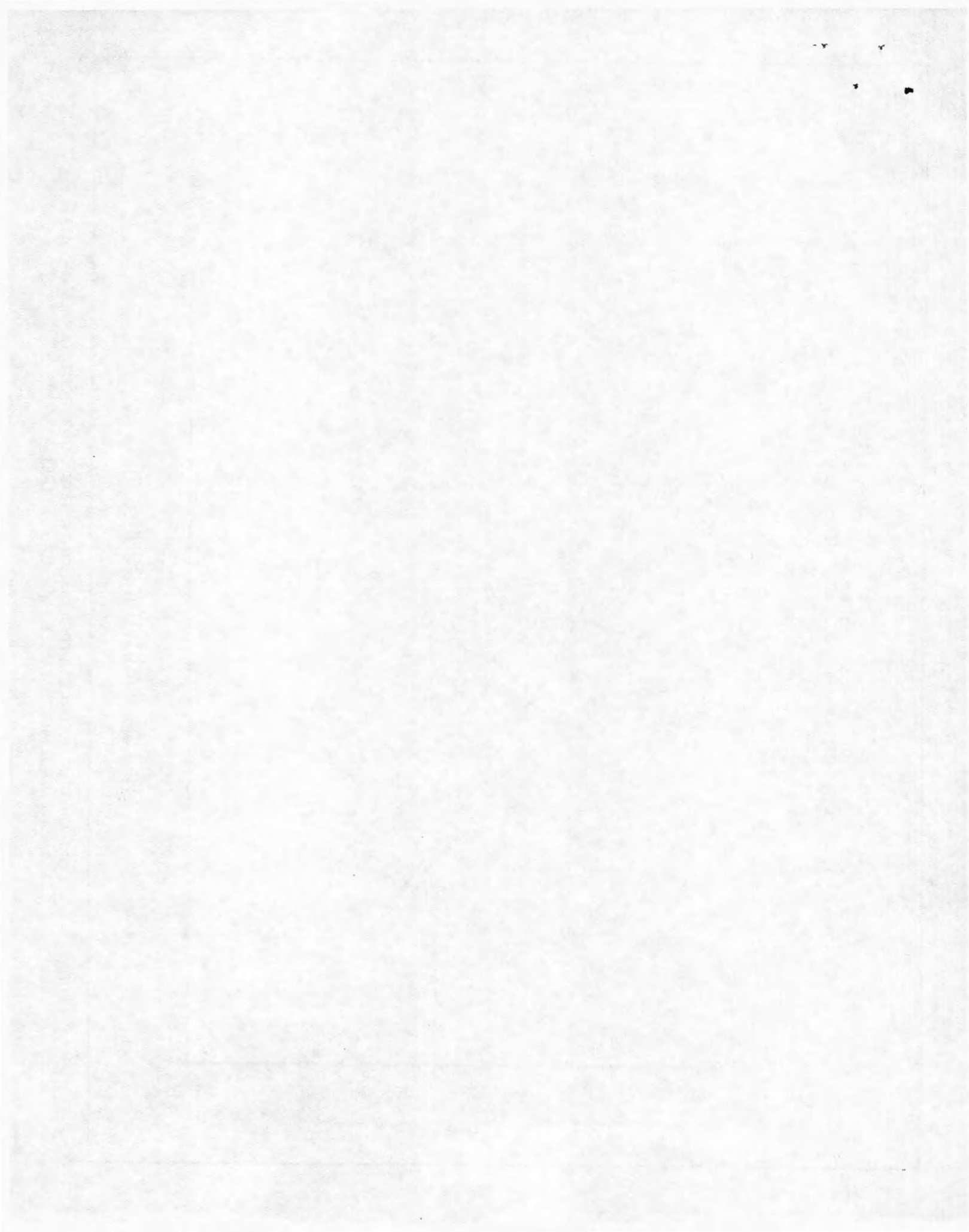


FIGURE B. COMPARATIVE SIGNAL STRENGTH DATA FOR 6094 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5295.2 FEET MSL.



MLS MATHEMATICAL MODELING PERFORMED BY:
FAA TECHNICAL CENTER, ACT-140
ATLANTIC CITY AIRPORT, NJ 08405
TITLE: RCVR = 11500, XMTR = 7.8 FT AM, RADIUS = 197050
RUN #: 5295 DATE: 16-MAR-88 11:16:40
RUNWAY: 17R AIRPORT: DENVER, COLORADO (STAPLETON)

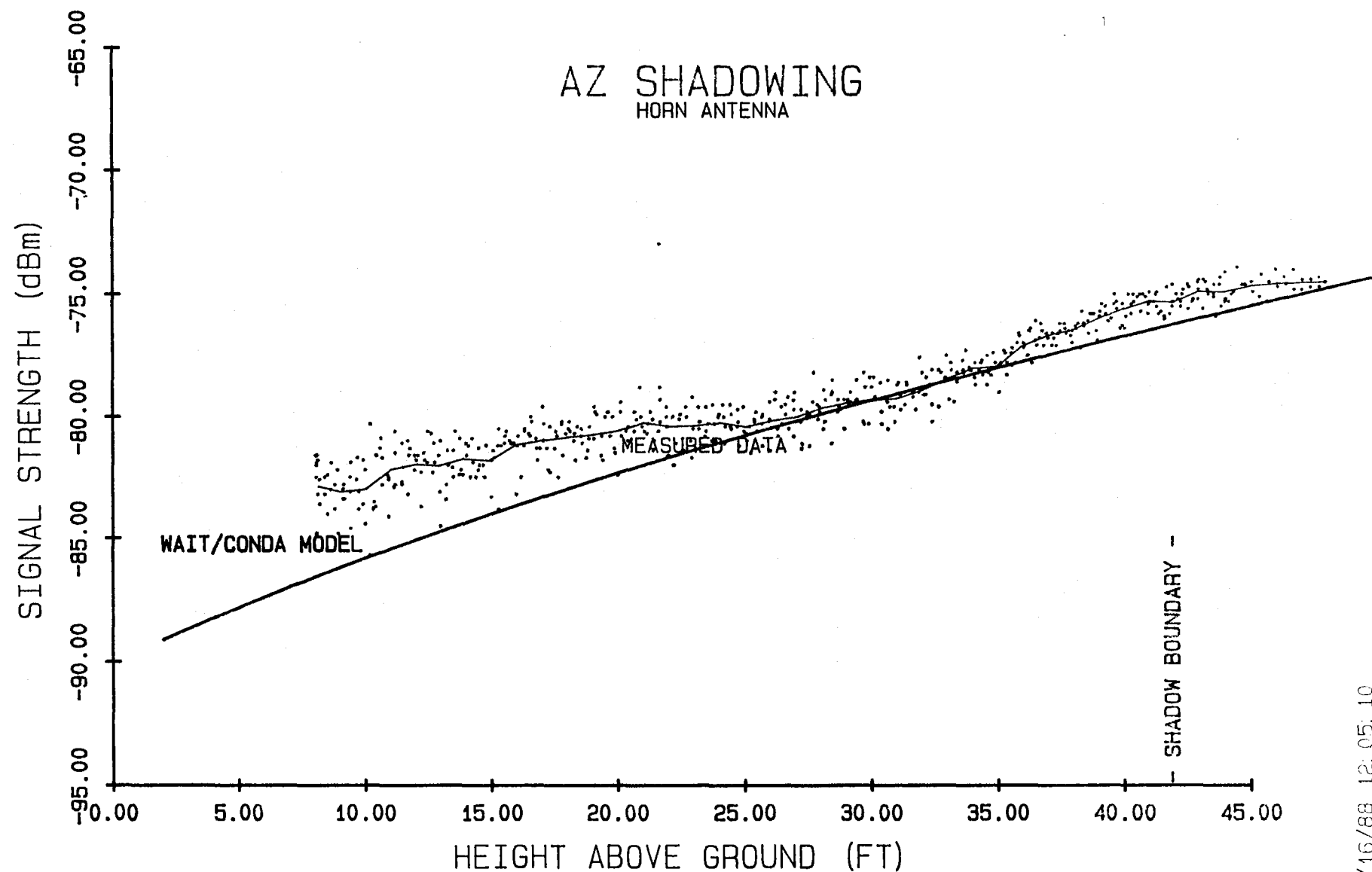


FIGURE 9. COMPARATIVE SIGNAL STRENGTH DATA FOR 11500 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5295.2 FEET MSL.

03/16/88 12:05:10

MLS MATHEMATICAL MODELING PERFORMED BY:
 FAA TECHNICAL CENTER, ACT-140
 ATLANTIC CITY AIRPORT, NJ 08405
 TITLE: RCVR = 6094 FT, XMTR = 10.2 FT AM, RADIUS = 197050
 RUN #: 5297 DATE: 16-MAR-88 11:14:03
 RUNWAY: 17R AIRPORT: DENVER, COLORADO (STAPLETON)

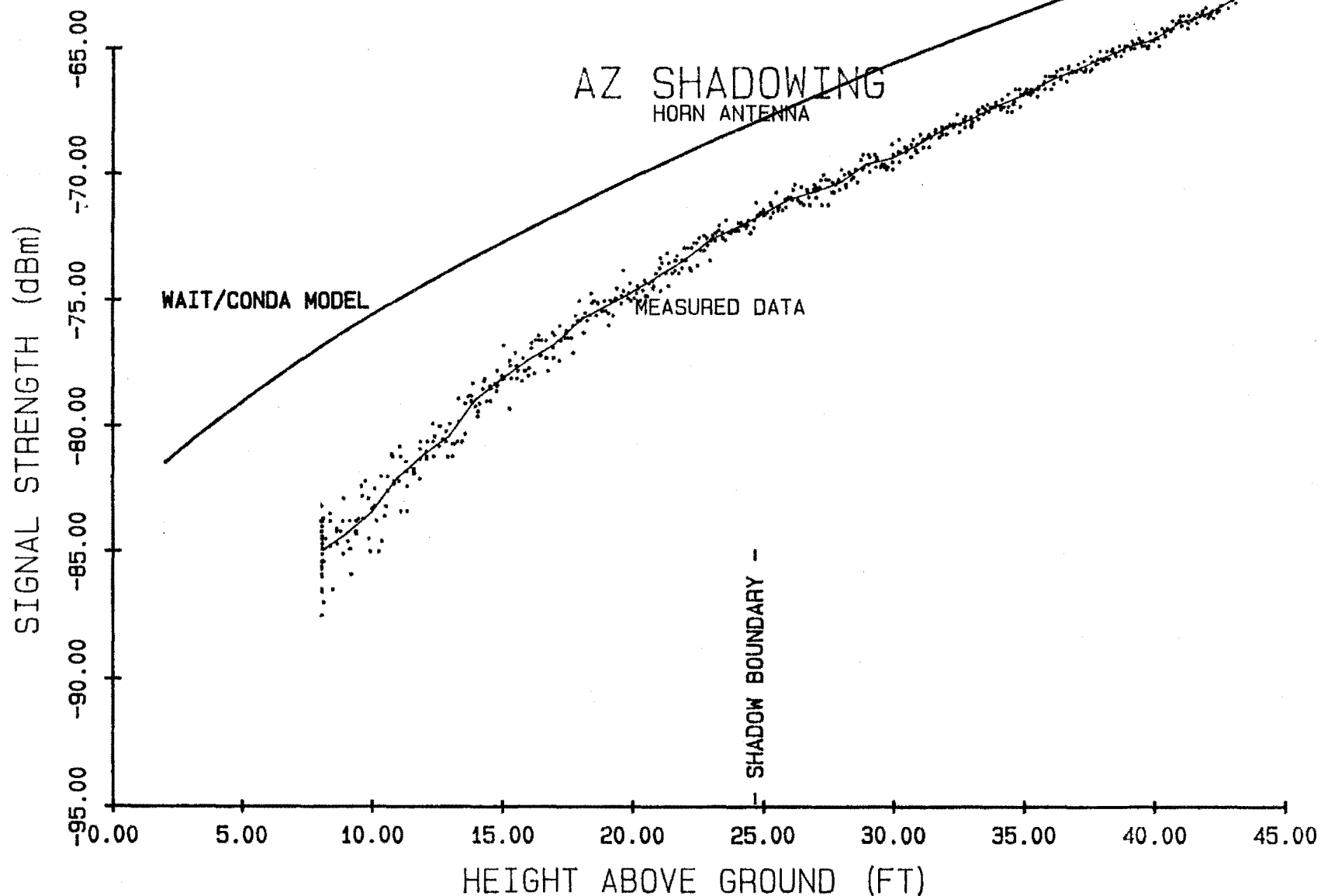
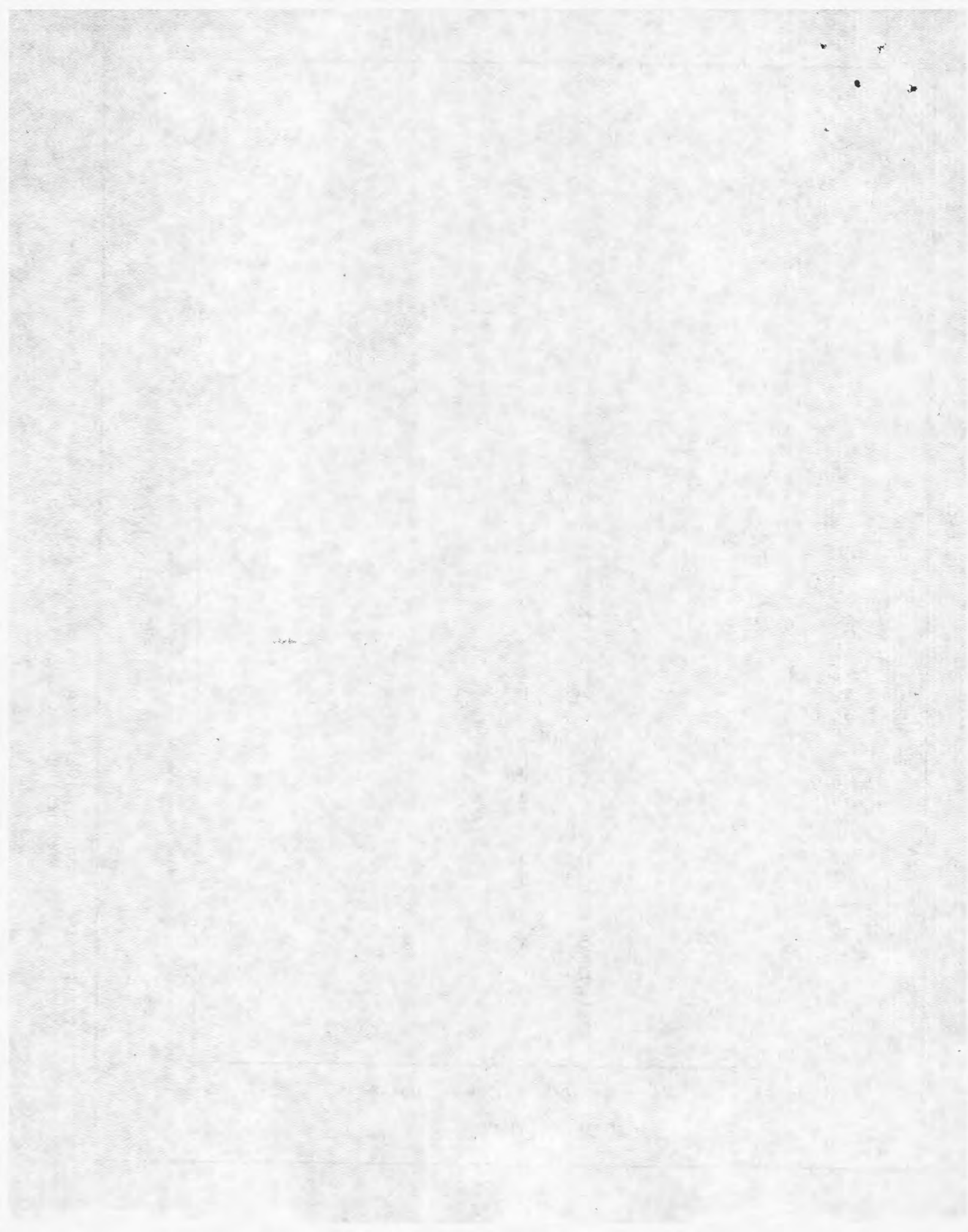


FIGURE 10. COMPARATIVE SIGNAL STRENGTH DATA FOR 6094 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5297.9 FEET MSL.

03/16/88 11:50.00



MLS MATHEMATICAL MODELING PERFORMED BY:
 FAA TECHNICAL CENTER, ACT-140
 ATLANTIC CITY AIRPORT, NJ 08405
 TITLE: RCVR = 11500, XMTR = 10.2 FT AM, RADIUS = 197050
 RUN #: 5297 DATE: 16-MAR-88 11:17:05
 RUNWAY: 17R AIRPORT: DENVER, COLORADO (STAPLETON)

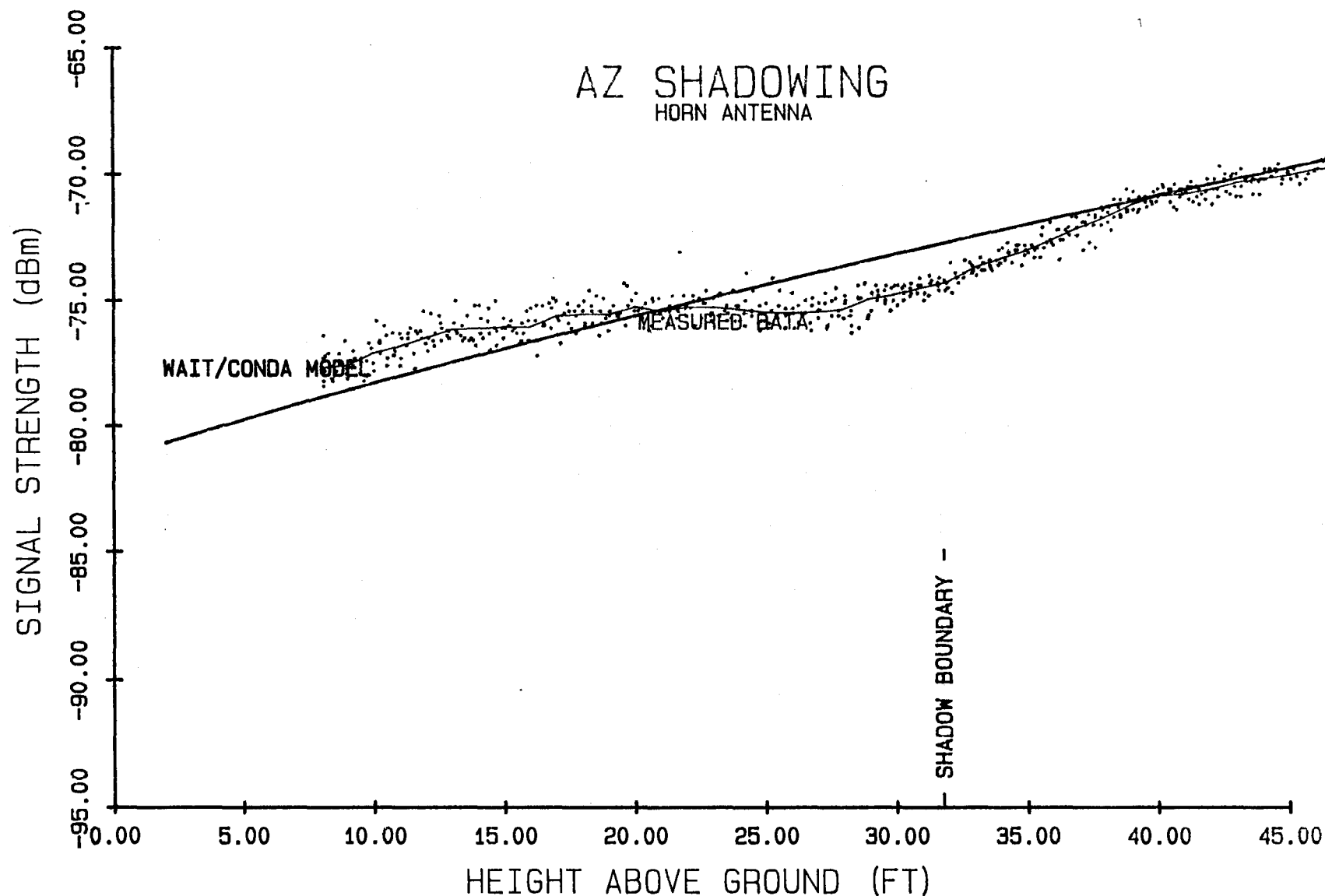


FIGURE 11. COMPARATIVE SIGNAL STRENGTH DATA FOR 11500 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5297.9 FEET MSL.

03/16/88 12:08:28

RUNWAY PROFILE & CYLINDRICAL HUMP DATA

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A: DEN17RZ.DAT

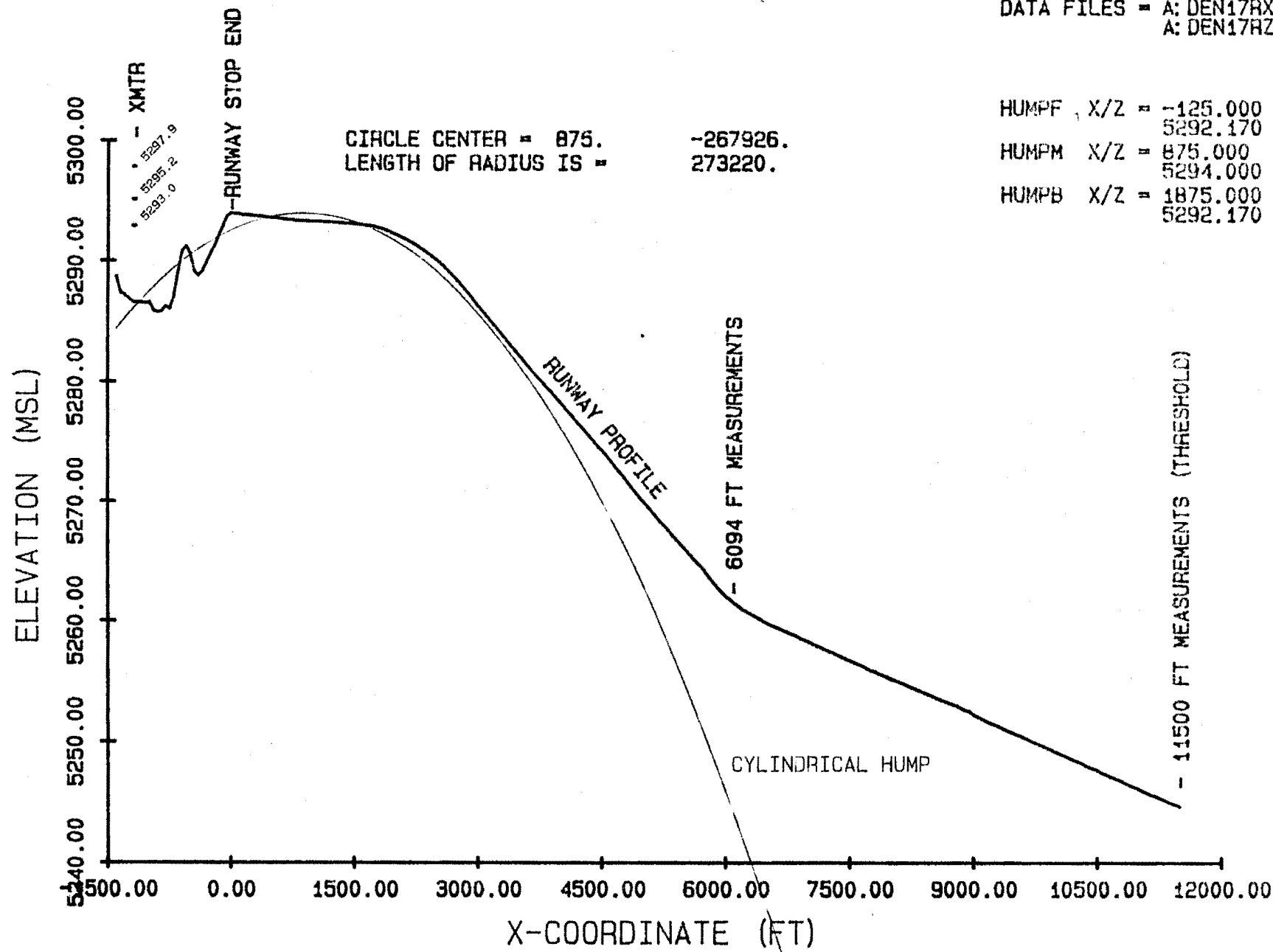
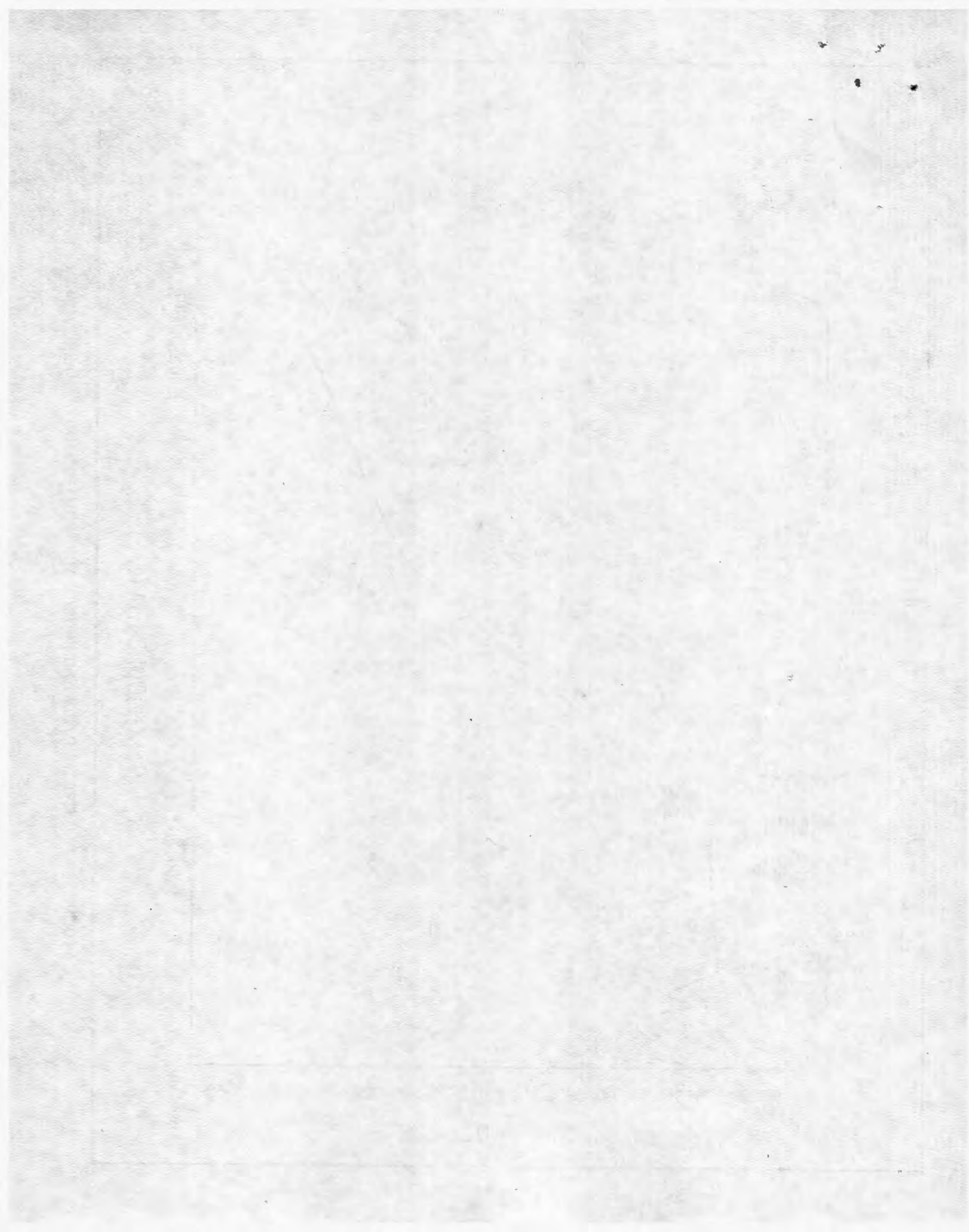


FIGURE 12. CYLINDRICAL HUMP PROFILE FOR RADIUS = 273220 FEET.



MLS MATHEMATICAL MODELING PERFORMED BY:
FAA TECHNICAL CENTER, ACT-140
ATLANTIC CITY AIRPORT, NJ 08405
TITLE: ACVR = 6094 FT, XMTR = 5.6 FT AM, RADIUS = 273220
RUN #: 5293 DATE: 16-MAR-88 11:20:11
RUNWAY: 17R AIRPORT: DENVER, COLORADO (STAPLETON)

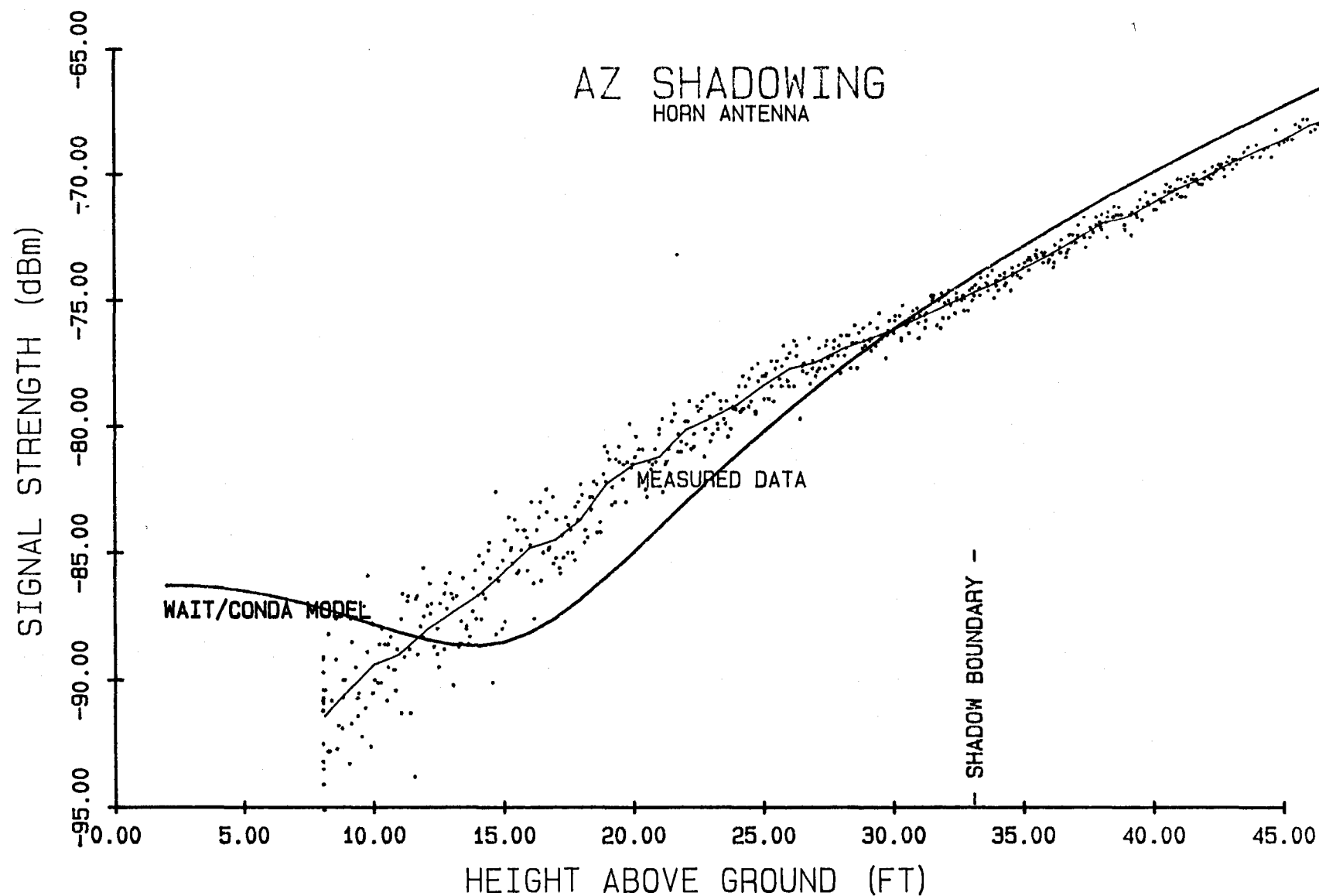


FIGURE 13. COMPARATIVE SIGNAL STRENGTH DATA FOR 6094 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5293.0 FEET MSL.

03/16/88 12:17:53

MLS MATHEMATICAL MODELING PERFORMED BY:
 FAA TECHNICAL CENTER, ACT-140
 ATLANTIC CITY AIRPORT, NJ 08405
 TITLE: RCVR = 11500, XMTR = 5.6 FT AM, RADIUS = 273220
 RUN #: 5293 DATE: 16-MAR-88 11:23:35
 RUNWAY: 17R AIRPORT: DENVER, COLORADO (STAPLETON)

AZ SHADOWING HORN ANTENNA

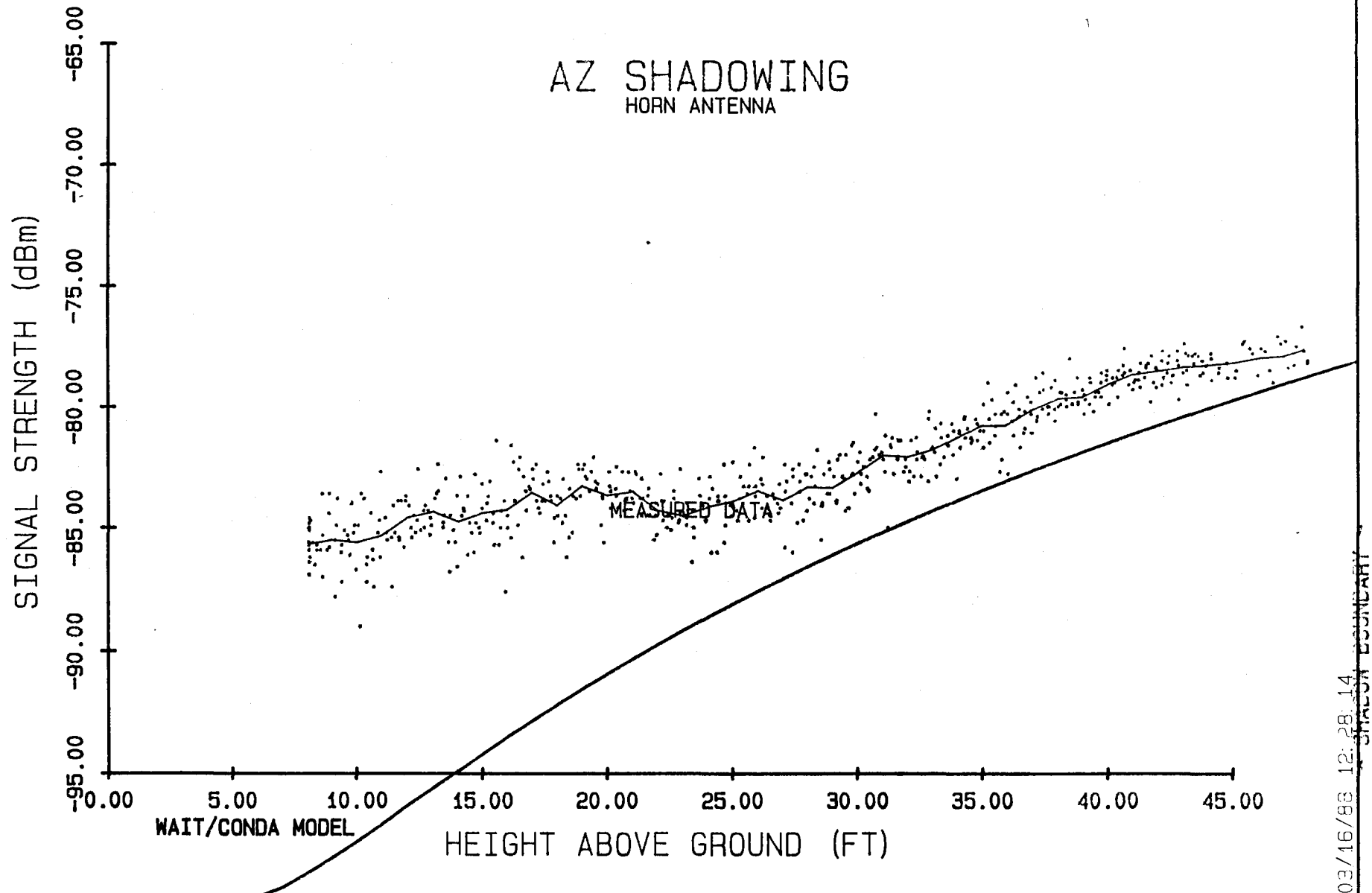
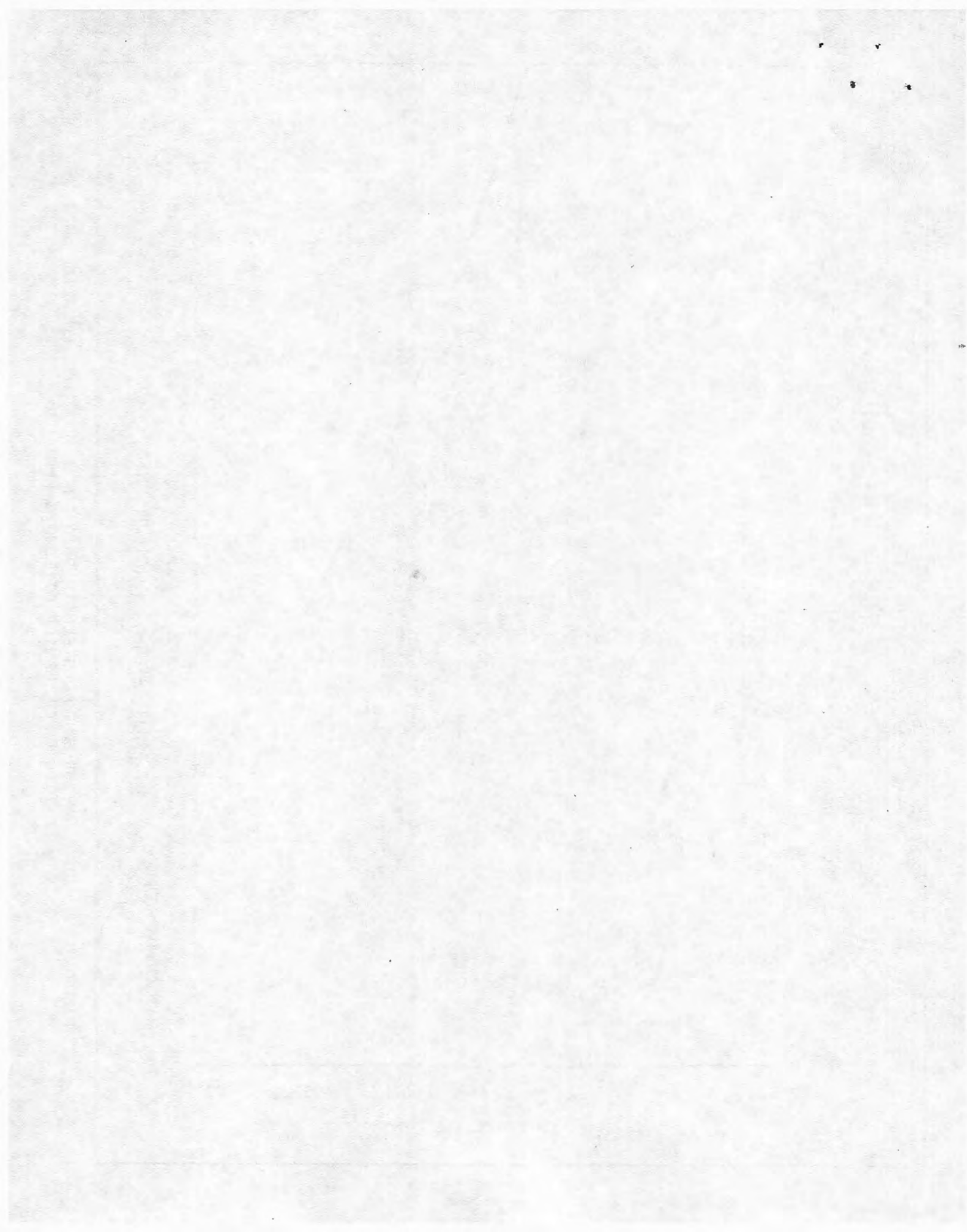


FIGURE 14. COMPARATIVE SIGNAL STRENGTH DATA FOR 11500 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5293.0 FEET MSL.

03/16/88 12:28:14
 SIGNAL STRENGTH



MLS MATHEMATICAL MODELING PERFORMED BY:
 FAA TECHNICAL CENTER, ACT-140
 ATLANTIC CITY AIRPORT, NJ 08405
 TITLE: RCVR = 6094 FT, XMTR = 7.8 FT AM, RADIUS = 273220
 RUN #: 5295 DATE: 16-MAR-88 11:20:30
 RUNWAY: 17R AIRPORT: DENVER, COLORADO (STAPLETON)

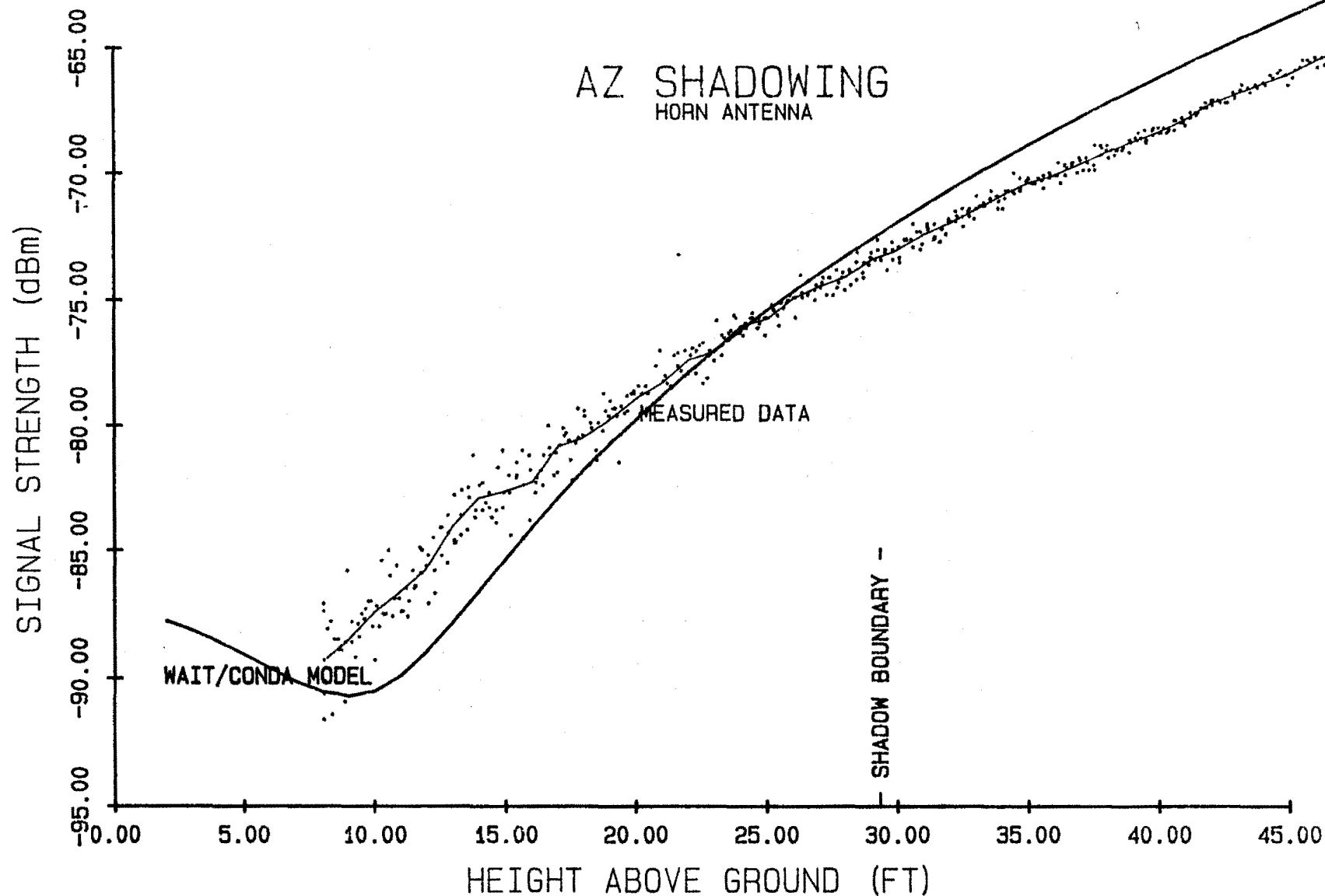


FIGURE 15. COMPARATIVE SIGNAL STRENGTH DATA FOR 6094 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5295.2 FEET MSL.

03/16/88 12:21:02

MLS MATHEMATICAL MODELING PERFORMED BY:
FAA TECHNICAL CENTER, ACT-140
ATLANTIC CITY AIRPORT, NJ 08405
TITLE: RCVR = 11500, XMTR = 7.8 FT AM, RADIUS = 273220
RUN #: 5295 DATE: 16-MAR-88 11:24:51
RUNWAY: 17R AIRPORT: DENVER, COLORADO (STAPLETON)

AZ SHADOWING HORN ANTENNA

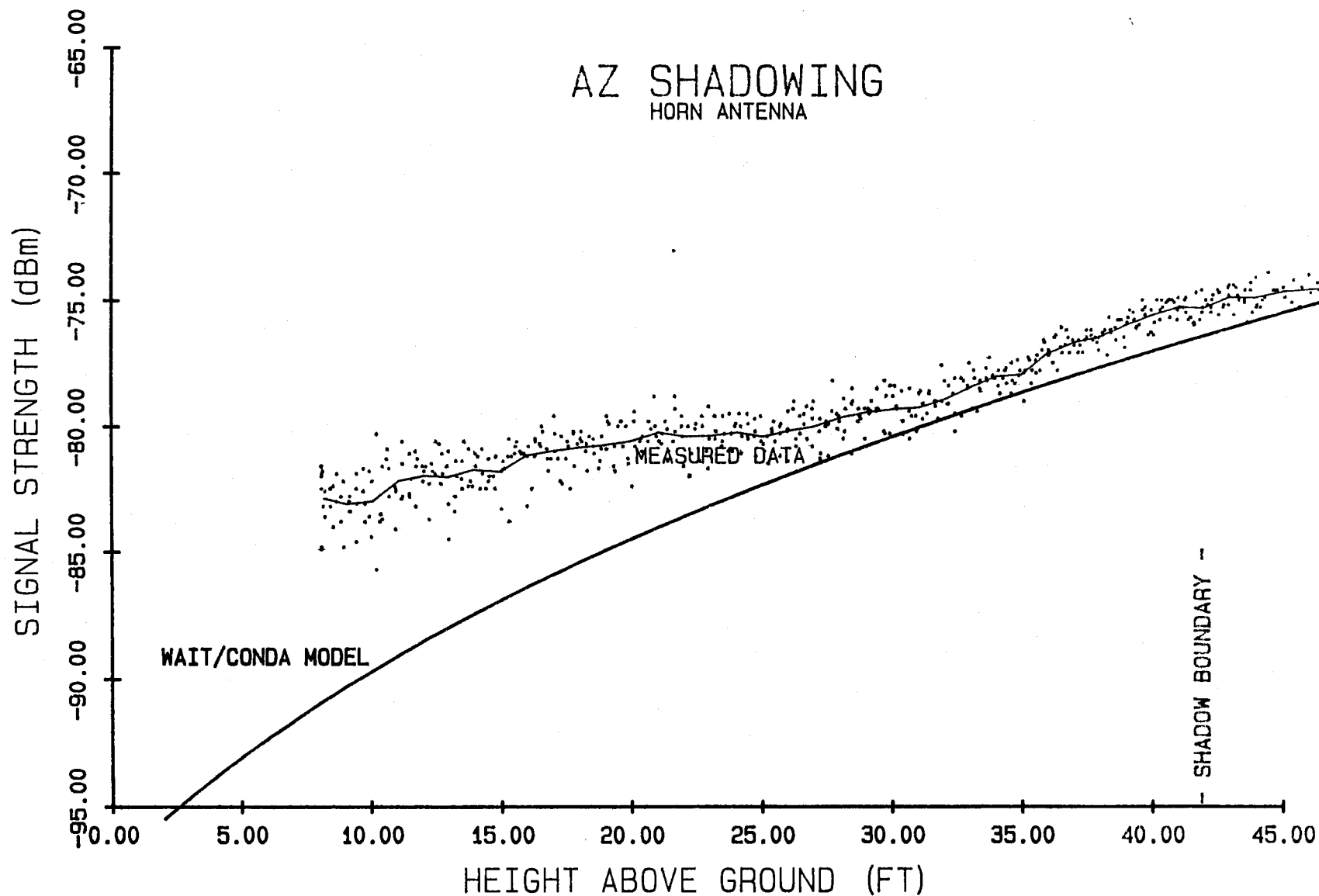


FIGURE 16. COMPARATIVE SIGNAL STRENGTH DATA FOR 11500 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5295.2 FEET MSL.

MLS MATHEMATICAL MODELING PERFORMED BY:
 FAA TECHNICAL CENTER, ACT-140
 ATLANTIC CITY AIRPORT, NJ 08405
 TITLE: RCVR = 6094 FT, XMTR = 10.2 FT AM, RADIUS = 273220
 RUN #: 5297 DATE: 16-MAR-88 11:20:50
 RUNWAY: 17R AIRPORT: DENVER, COLORADO (STAPLETON)

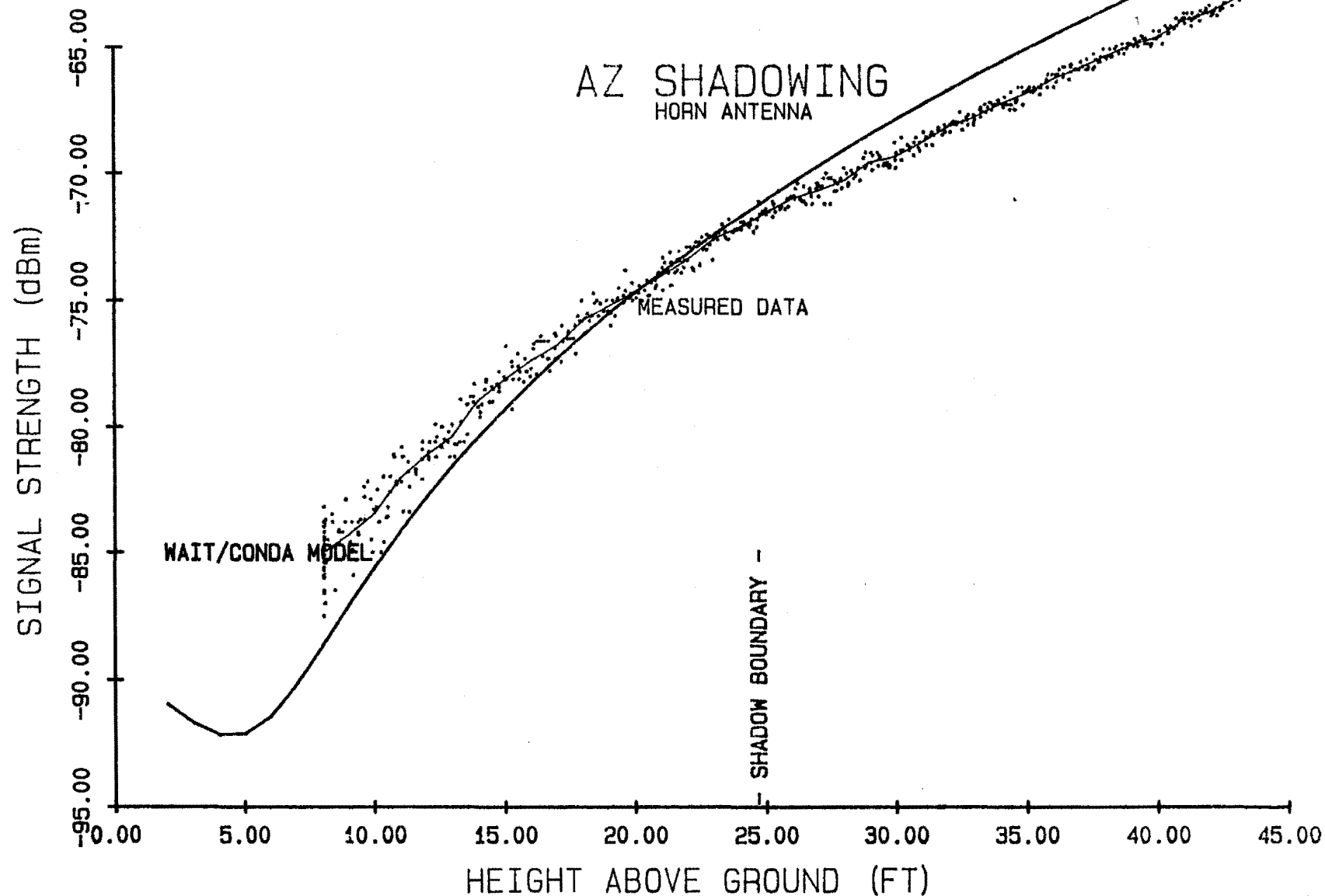
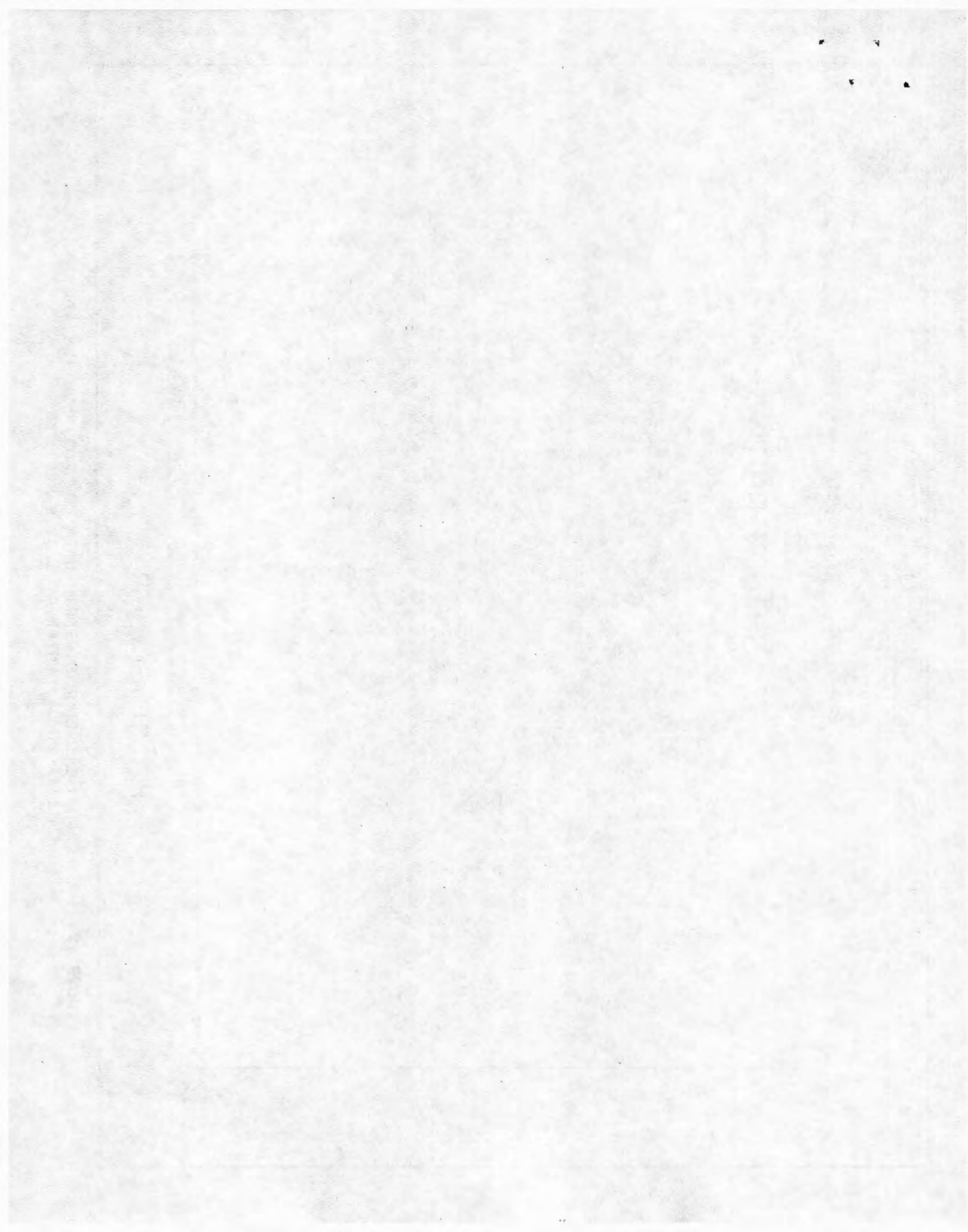


FIGURE 17. COMPARATIVE SIGNAL STRENGTH DATA FOR 6094 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5297.9 FEET MSL.

03/16/88 12:24:24



MLS MATHEMATICAL MODELING PERFORMED BY:
FAA TECHNICAL CENTER, ACT-140
ATLANTIC CITY AIRPORT, NJ 08405
TITLE: RCVR = 11500, XMTR = 10.2 FT AM, RADIUS = 273220
RUN #: 5297 DATE: 16-MAR-88 11:25:15
RUNWAY: 17R AIRPORT: DENVER, COLORADO (STAPLETON)

AZ SHADOWING HORN ANTENNA

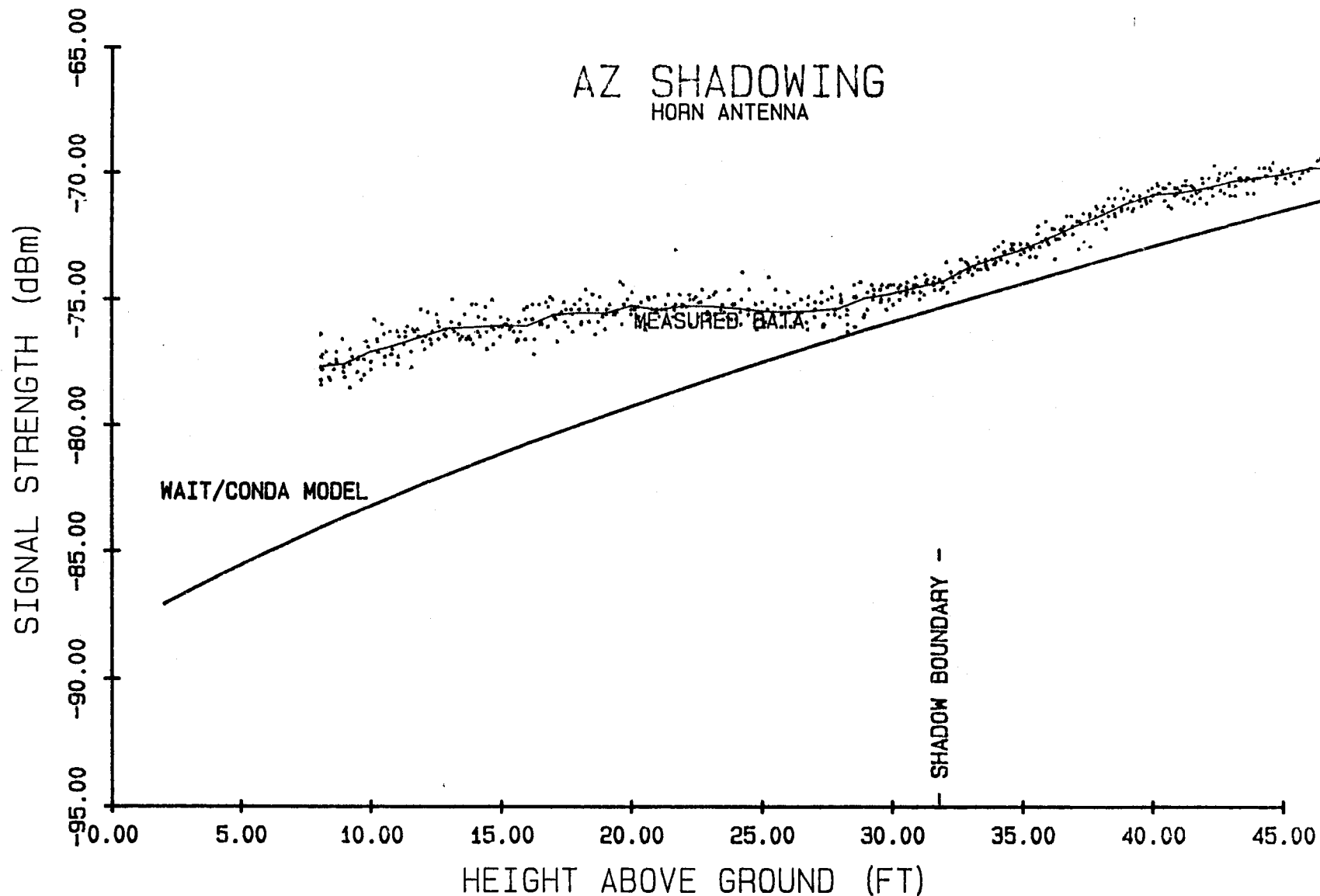


FIGURE 18. COMPARATIVE SIGNAL STRENGTH DATA FOR 11500 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5297.9 FEET MSL.

RUNWAY PROFILE REGRESSION LINE DATA

THE COORDINATES ON THE LINES ARE AS FOLLOWS:

STOP END =	1499.411	5293.371
INTERSECTION =	2256.670	5291.591
THRESHOLD =	2991.549	5286.774
MIDPOINTS	1878.040	2624.109
CLOSEST X	1896.520	2643.008

CIRCLE CENTER =	1461.	-172101.
LENGTH OF RADIUS IS =	177395.	
LENGTH OF BEST RADIUS IS =	177395.	

DATA FILES =	A: DEN17RX.DAT
	A: DEN17RZ.DAT
STOP END =	1499.411
PEAK =	2245.485
THRESHOLD =	2991.549
HUMPF X/Z =	461.315
	5290.556
HUMPM X/Z =	1461.315
	5293.375
HUMPB X/Z =	2461.314
	5290.556

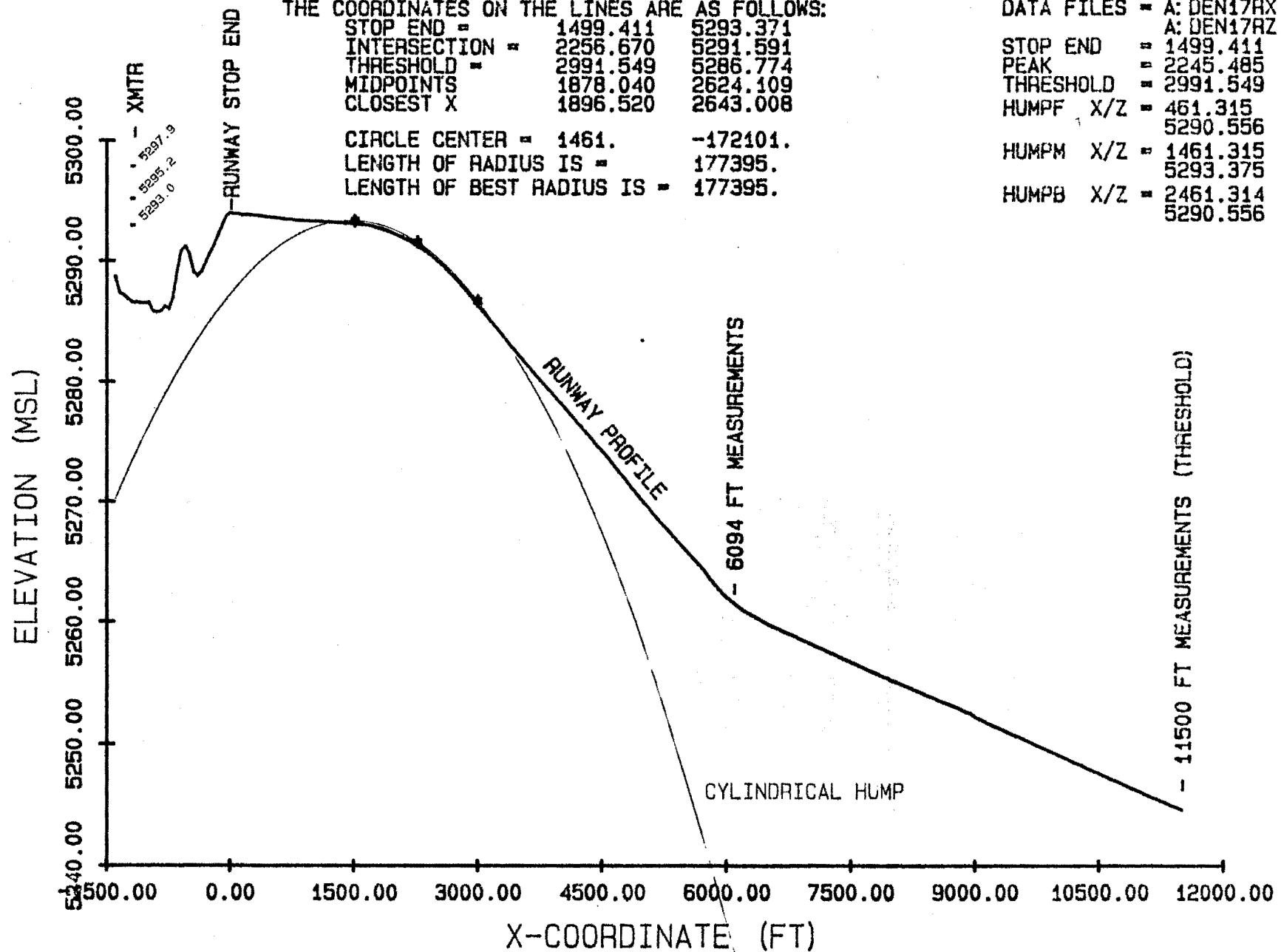
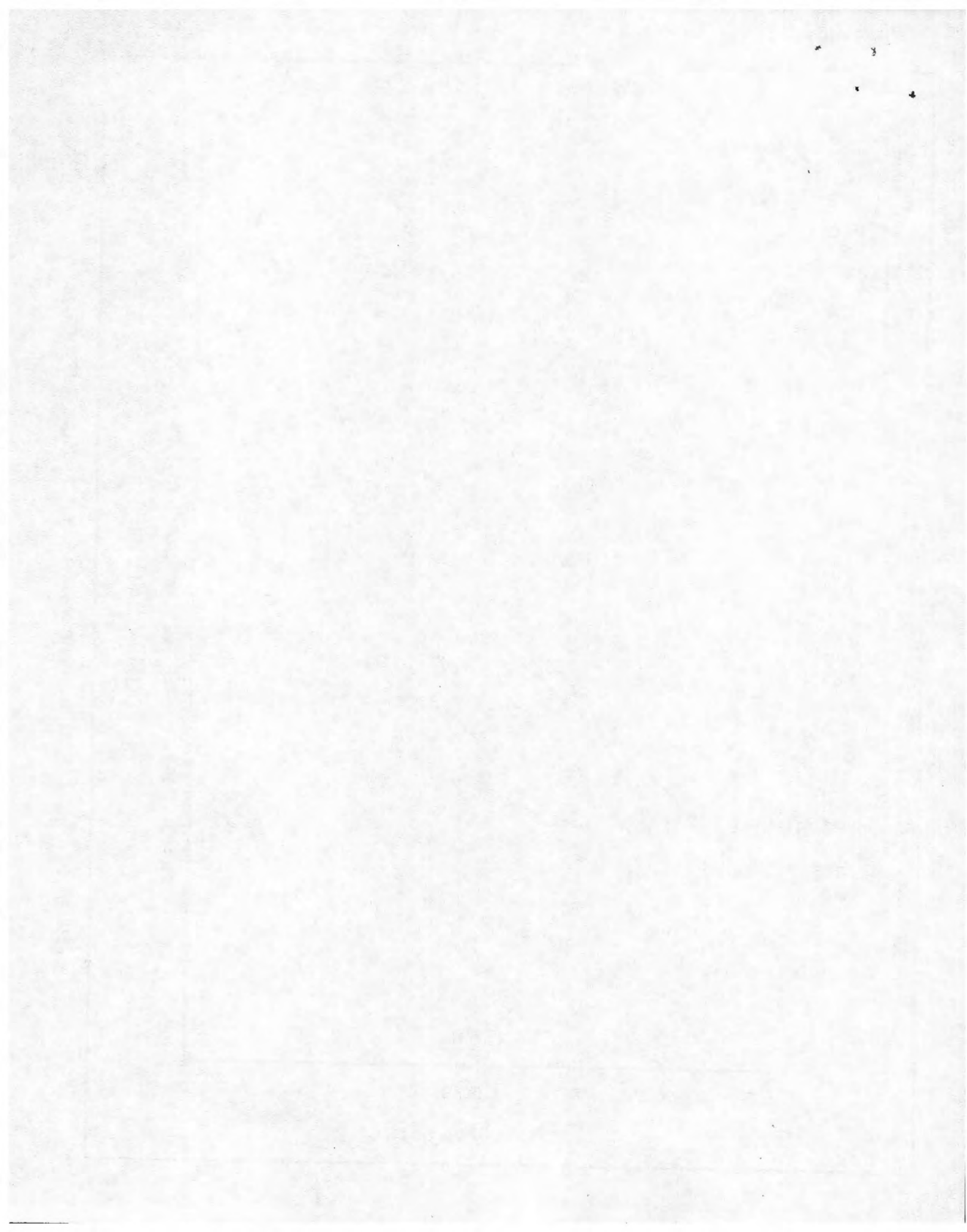


FIGURE 19. CYLINDRICAL HUMP PROFILE FOR RADIUS = 177395 FEET.



MLS MATHEMATICAL MODELING PERFORMED BY:
 FAA TECHNICAL CENTER, ACT-140
 ATLANTIC CITY AIRPORT, NJ 08405
 TITLE: RCVR = 6094 FT, XMTR = 5.6 FT AM, RADIUS = 177395
 RUN #: 5293 DATE: 16-MAR-88 11:05:56
 RUNWAY: 17R AIRPORT: DENVER, COLORADO-STAPLETON

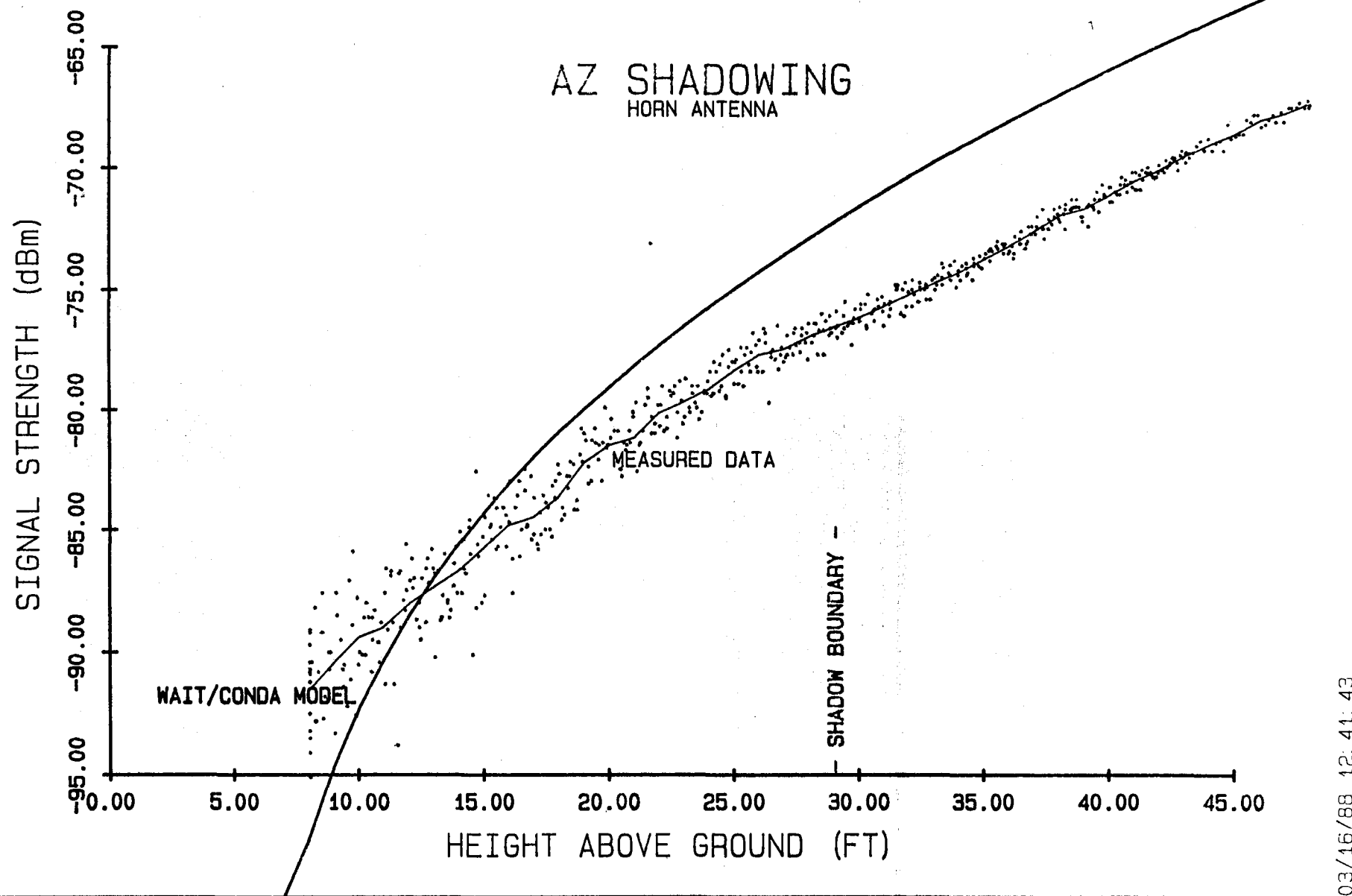


FIGURE 20. COMPARATIVE SIGNAL STRENGTH DATA FOR 6094 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5293.0 FEET MSL.

03/16/88 12:41:43

MLS MATHEMATICAL MODELING PERFORMED BY:
FAA TECHNICAL CENTER, ACT-140
ATLANTIC CITY AIRPORT, NJ 08405
TITLE: RCVR = 11500 XMTR = 5.60 FT AM, RADIUS = 177395
RUN #: 5293 DATE: 16-MAR-88 11:10:51
RUNWAY: 17R AIRPORT: DENVER, COLORADO (STAPLETON)

AZ SHADOWING HORN ANTENNA

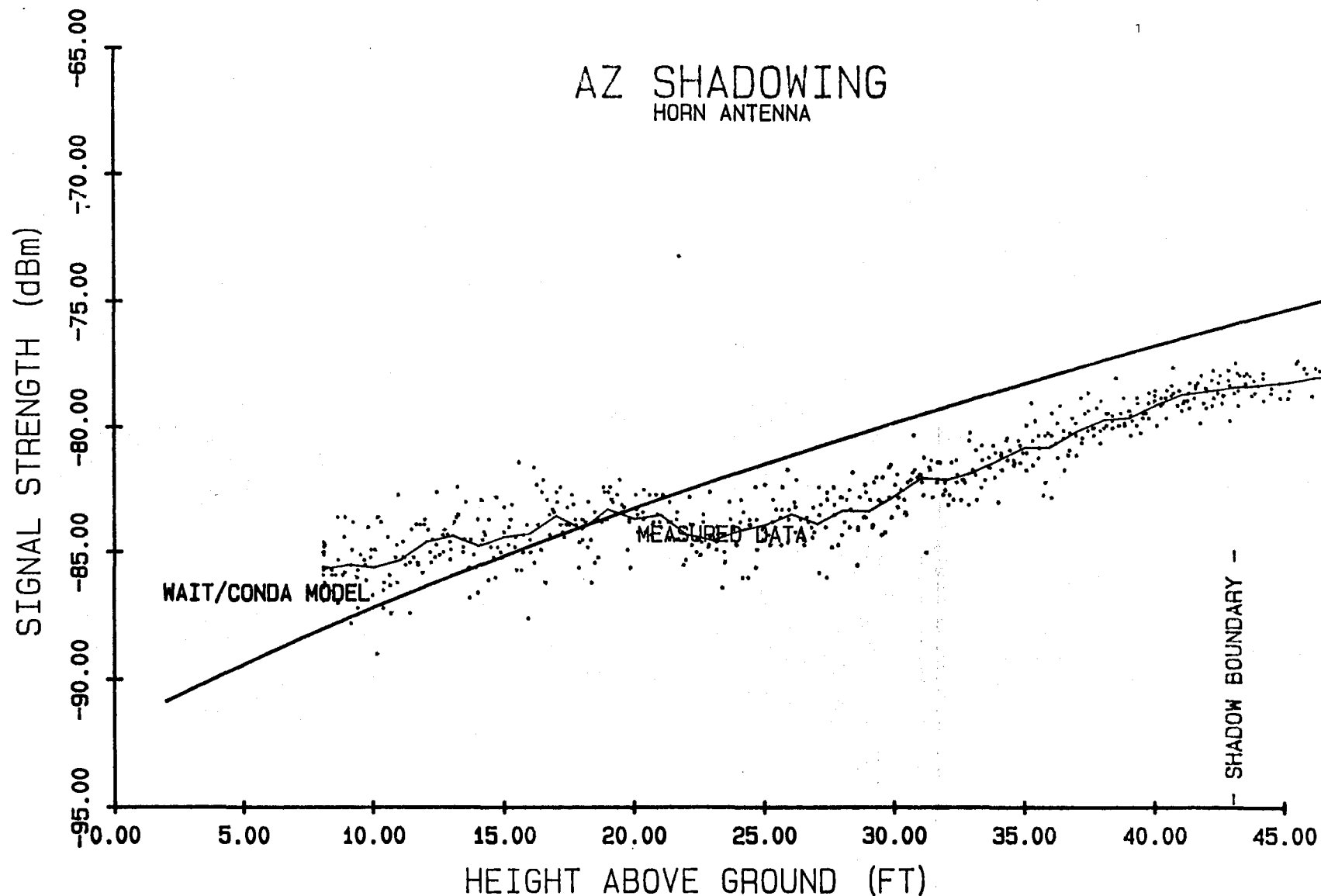


FIGURE 21. COMPARATIVE SIGNAL STRENGTH DATA FOR 11500 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5293.0 FEET MSL.

03/16/88 12:52:57

MLS MATHEMATICAL MODELING PERFORMED BY:
 FAA TECHNICAL CENTER, ACT-140
 ATLANTIC CITY AIRPORT, NJ 08405
 TITLE: RCVR = 6094 XMTR = 7.8 FT AM, RADIUS = 177395
 RUN #: 5295 DATE: 16-MAR-88 11:06:17
 RUNWAY: 17R AIRPORT: DENVER, COLORADO (STAPLETON)

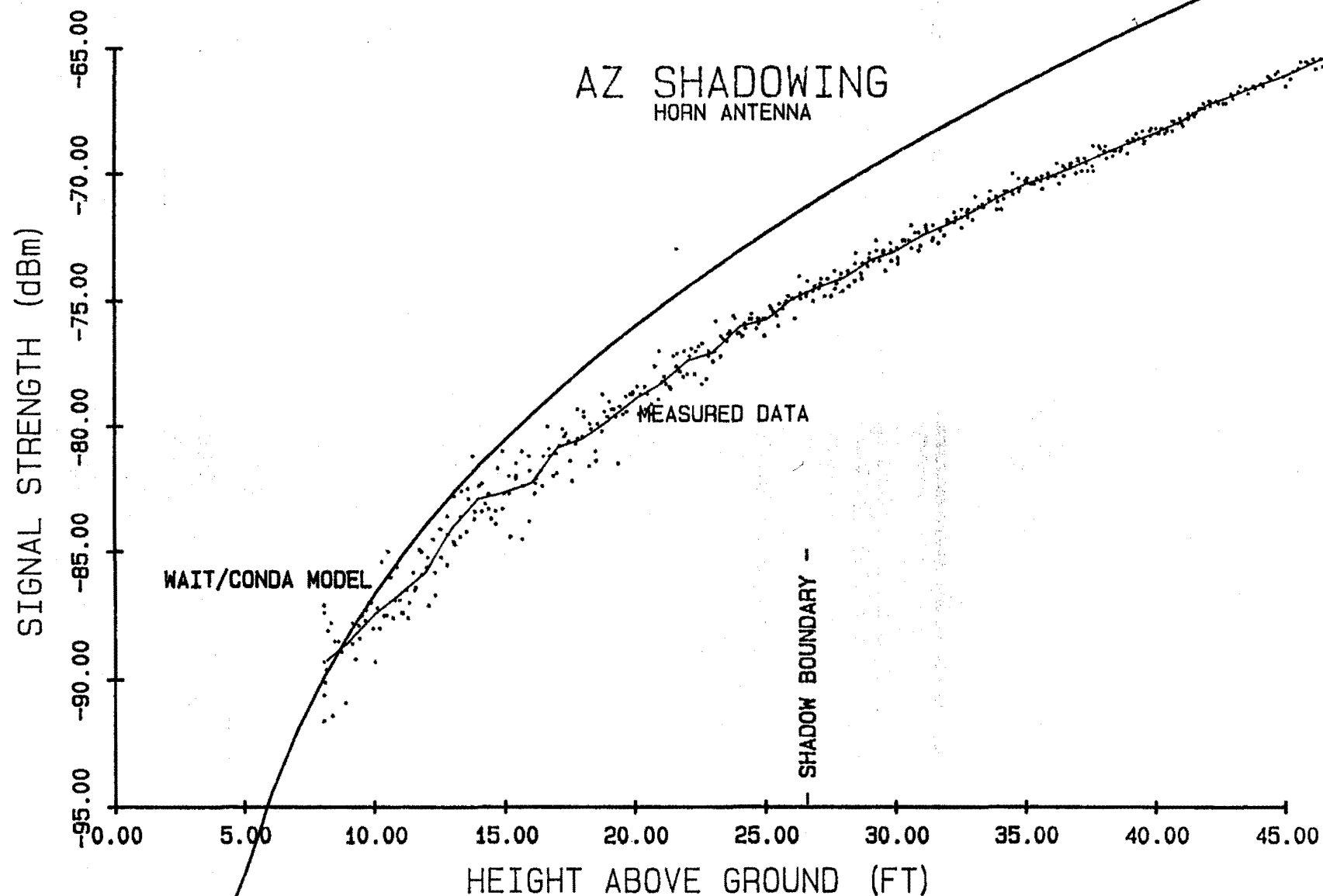


FIGURE 22. COMPARATIVE SIGNAL STRENGTH DATA FOR 6094 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5295.2 FEET MSL.

03/16/88 12:44:51

MLS MATHEMATICAL MODELING PERFORMED BY:
FAA TECHNICAL CENTER, ACT-140
ATLANTIC CITY AIRPORT, NJ 08405
TITLE: RCVR = 11500 XMTR = 7.80 FT AM, RADIUS = 177395
RUN #: 5295 DATE: 16-MAR-88 11:11:16
RUNWAY: 17R AIRPORT: DENVER, COLORADO-STAPLETON

AZ SHADOWING HORN ANTENNA

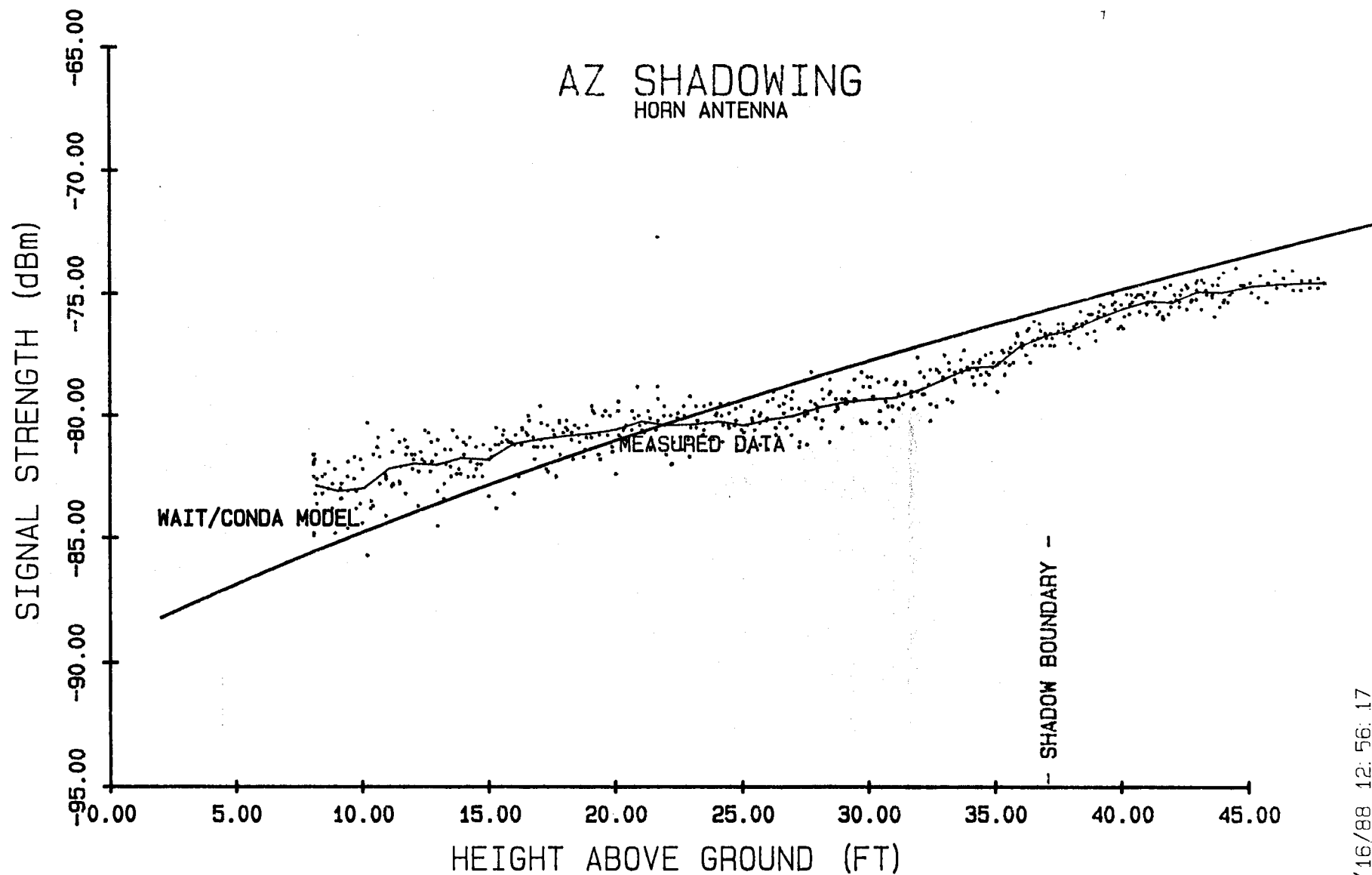


FIGURE 23. COMPARATIVE SIGNAL STRENGTH DATA FOR 11500 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5295.2 FEET MSL.

MLS MATHEMATICAL MODELING PERFORMED BY:
 FAA TECHNICAL CENTER, ACT-140
 ATLANTIC CITY AIRPORT, NJ 08405
 TITLE: RCVR = 6094 FT, XMTR = 10.5 FT AM, RADIUS = 177395
 RUN #: 5297 DATE: 16-MAR-88 11:06:38
 RUNWAY: 17R AIRPORT: DENVER, COLORADO (STAPLETON)

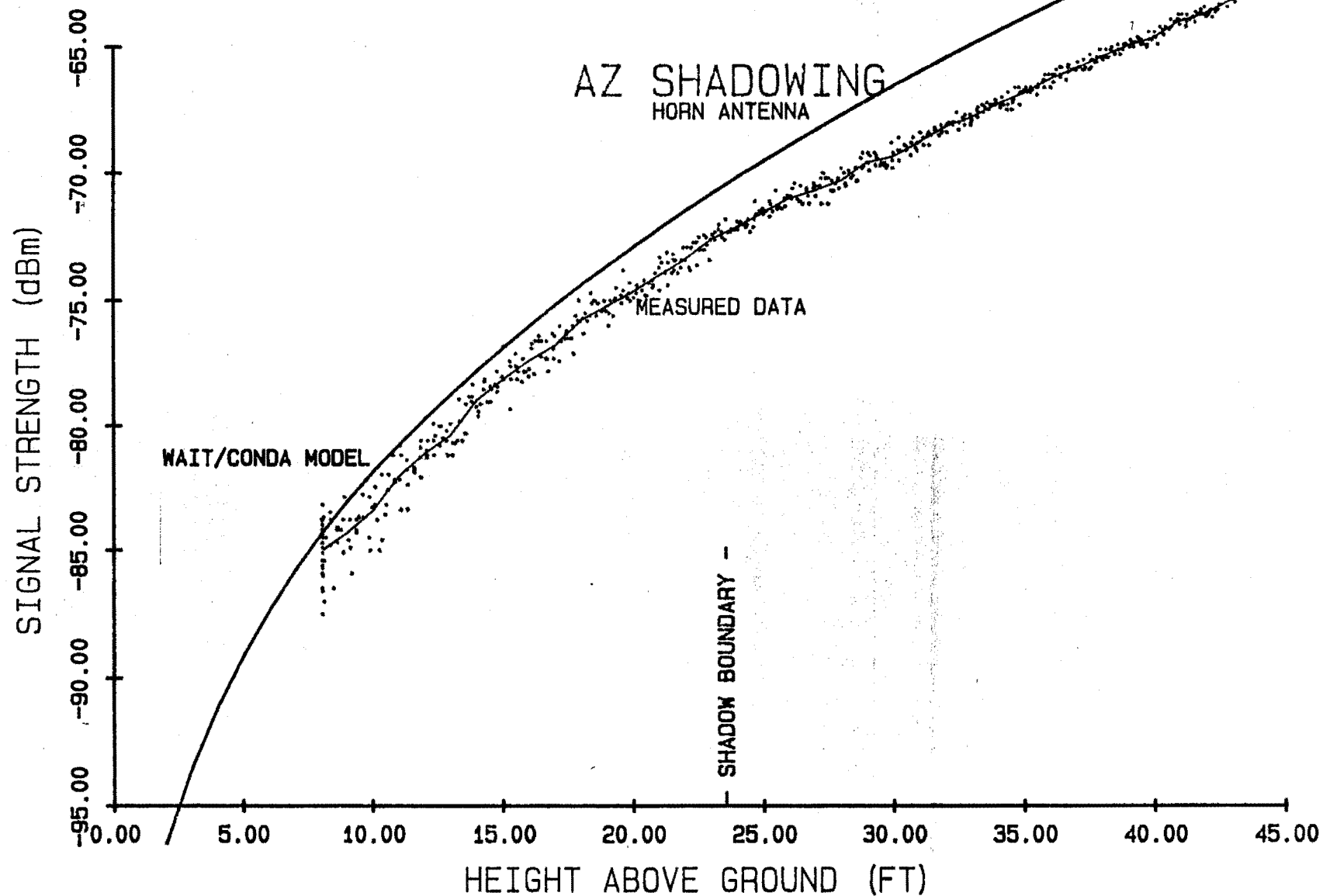


FIGURE 24. COMPARATIVE SIGNAL STRENGTH DATA FOR 6094 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5297.9 FEET MSL.

03/16/88 12:48.14

MLS MATHEMATICAL MODELING PERFORMED BY:
FAA TECHNICAL CENTER, ACT-140
ATLANTIC CITY AIRPORT, NJ 08405
TITLE: RCVR = 11500 XMTR = 10.5 FT AM, RADIUS = 177395
RUN #: 5297 DATE: 16-MAR-88 11:11:40
RUNWAY: 17R AIRPORT: DENVER, COLORADO-STAPLETON

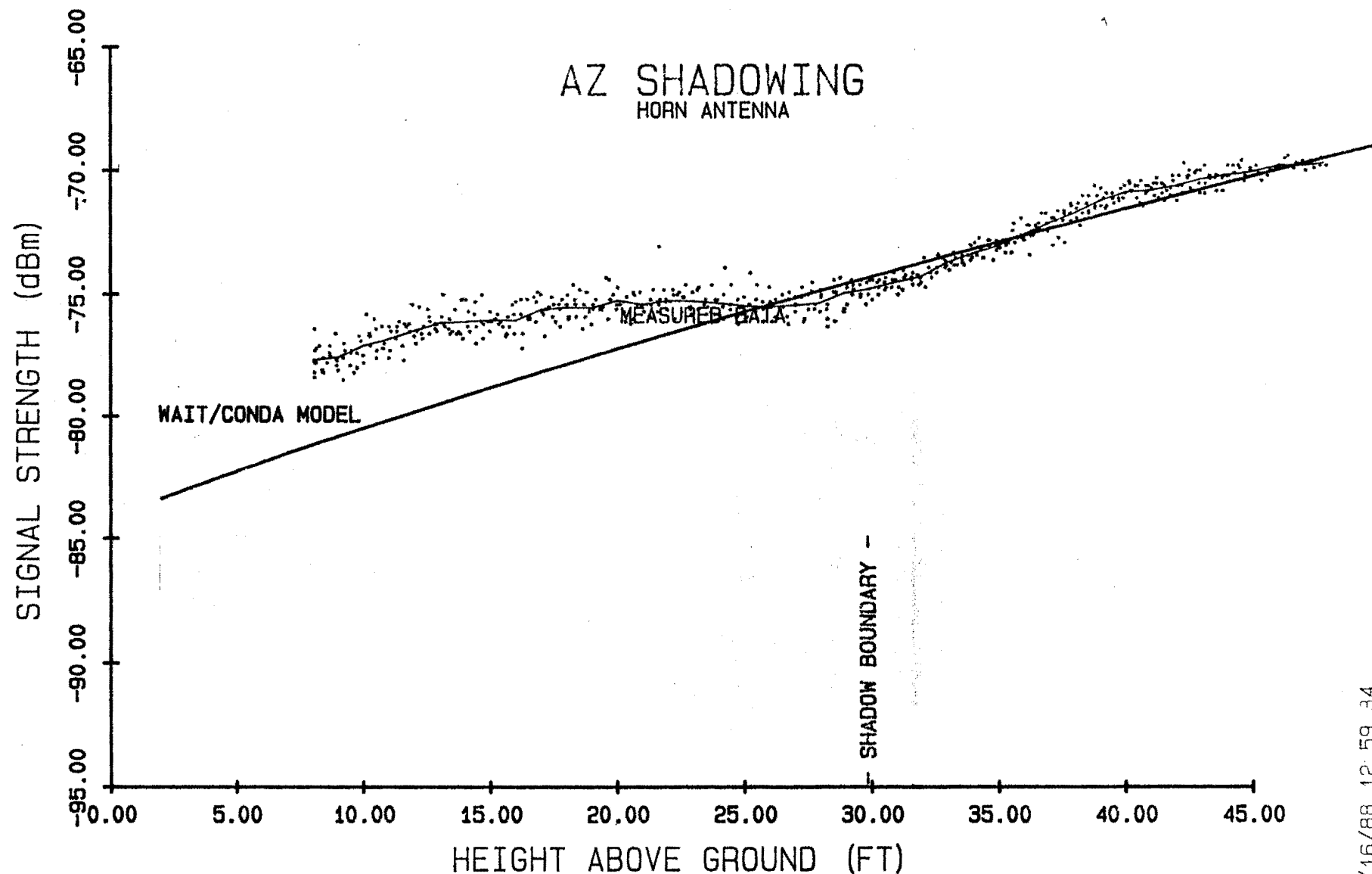


FIGURE 25. COMPARATIVE SIGNAL STRENGTH DATA FOR 11500 FOOT LOCATION WITH TRANSMITTER PHASE CENTER AT 5297.9 FEET MSL.

03/16/88 12:59:34

MLS MATHEMATICAL MODELING PERFORMED BY:
FAA TECHNICAL CENTER, ACT-140
ATLANTIC CITY AIRPORT, NJ 08405
TITLE: SIGNAL LEVEL 8 FT ABOVE RUNWAY, RADIUS = 177395
RUN #: 5295 DATE: 17-MAR-88 11:01:11
RUNWAY: 17R AIRPORT: DENVER, COLORADO-STAPLETON

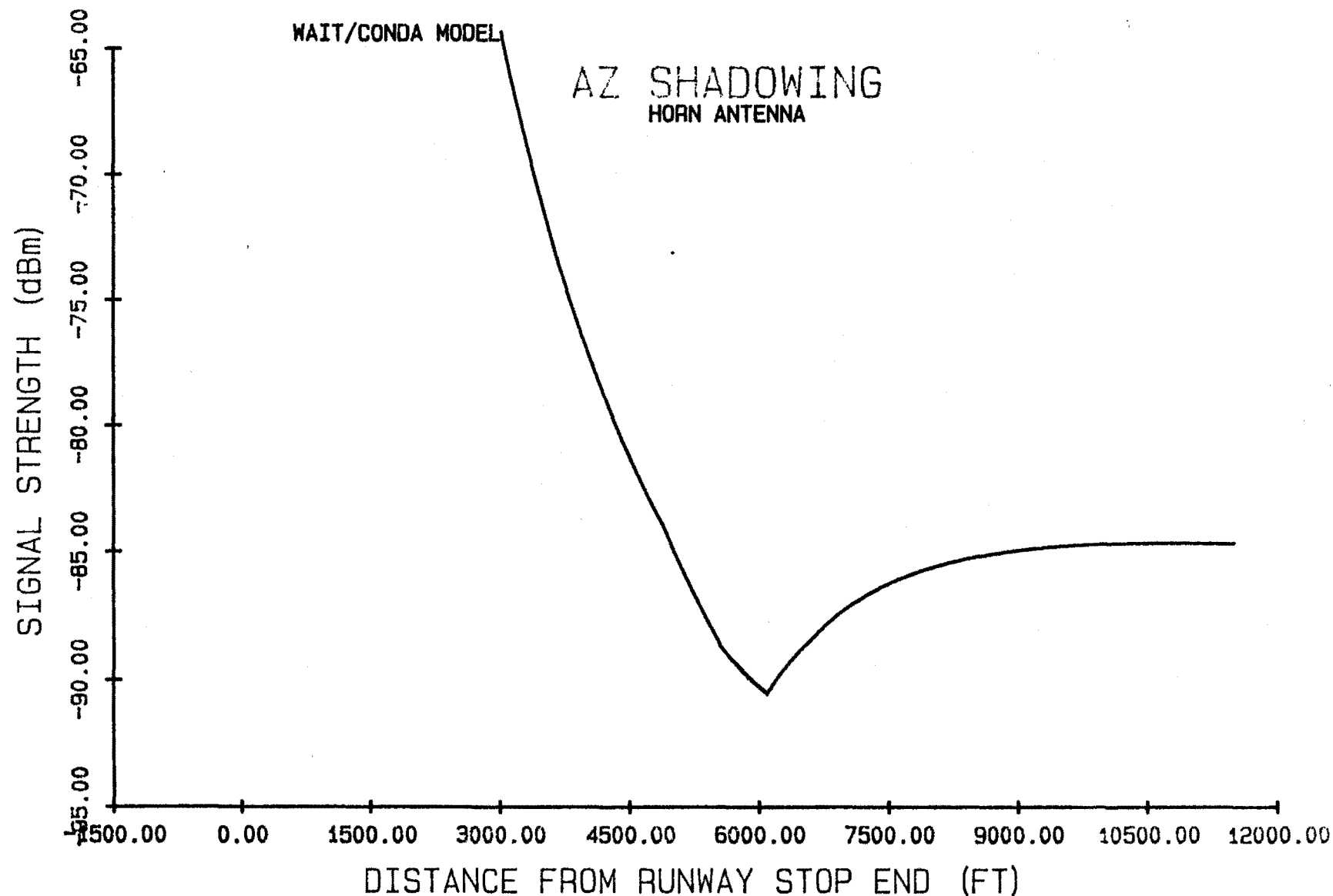
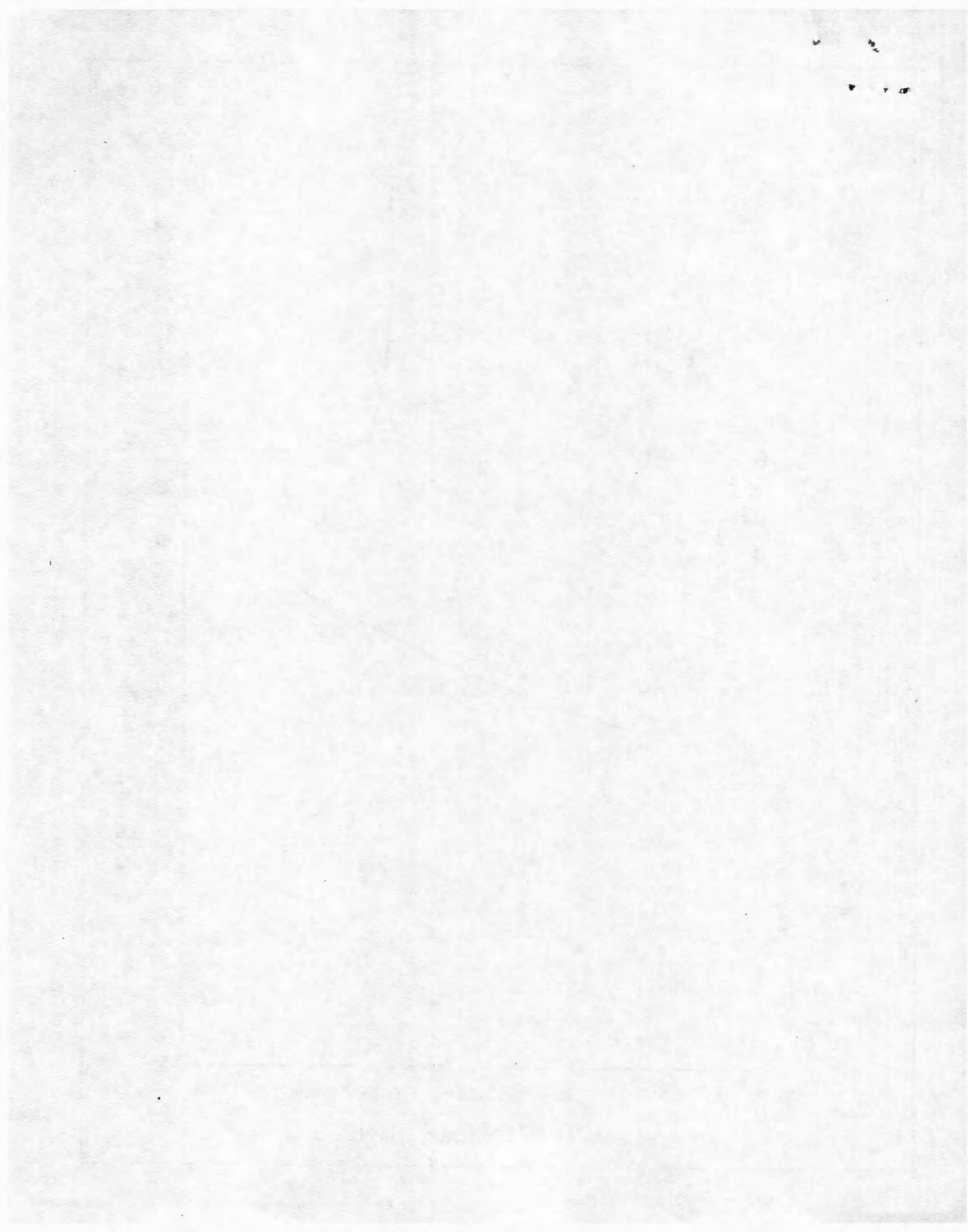


FIGURE 26. SIGNAL STRENGTH 8 FEET ABOVE RUNWAY SURFACE WITH HORN ANTENNA FOR CYLINDER RADIUS OF 177395 FEET AND PHASE CENTER AT 5295.2 FEET.



MLS MATHEMATICAL MODELING PERFORMED BY:
FAA TECHNICAL CENTER, ACT-140
ATLANTIC CITY AIRPORT, NJ 08405
TITLE: SIGNAL LEVEL 8 FT ABOVE RUNWAY, RADIUS = 177395
RUN #: 5295 DATE: 17-MAR-88 11:01:11
RUNWAY: 17R AIRPORT: DENVER, COLORADO-STAPLETON

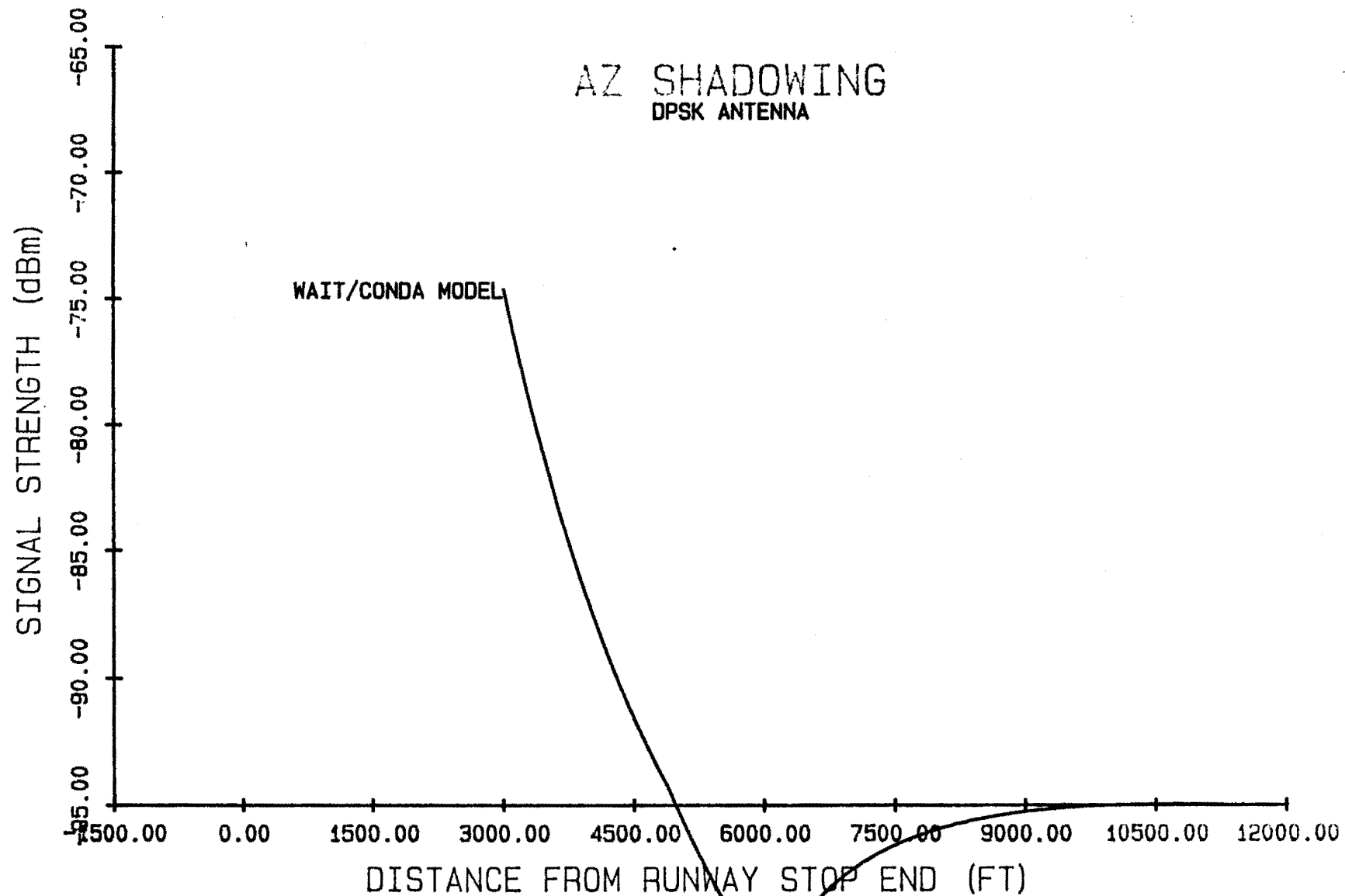


FIGURE 27. SIGNAL STRENGTH 8 FEET ABOVE RUNWAY SURFACE WITH DPSK ANTENNA FOR CYLINDER RADIUS OF 177395 FEET AND PHASE CENTER AT 5295.2 FEET.

03/17/88 11:14:11

2 2
3 4 5

MLS MATHEMATICAL MODELING PERFORMED BY:
FAA TECHNICAL CENTER, ACT-140
ATLANTIC CITY AIRPORT, NJ 08405
TITLE: SIGNAL LEVEL 8 FT ABOVE RUNWAY, RADIUS = 177395
RUN # 5297 DATE: 17-MAR-88 10:33:33
WAIT/CONDA MODEL
RUNWAY: 17R AIRPORT: DENVER, COLORADO-STAPLETON

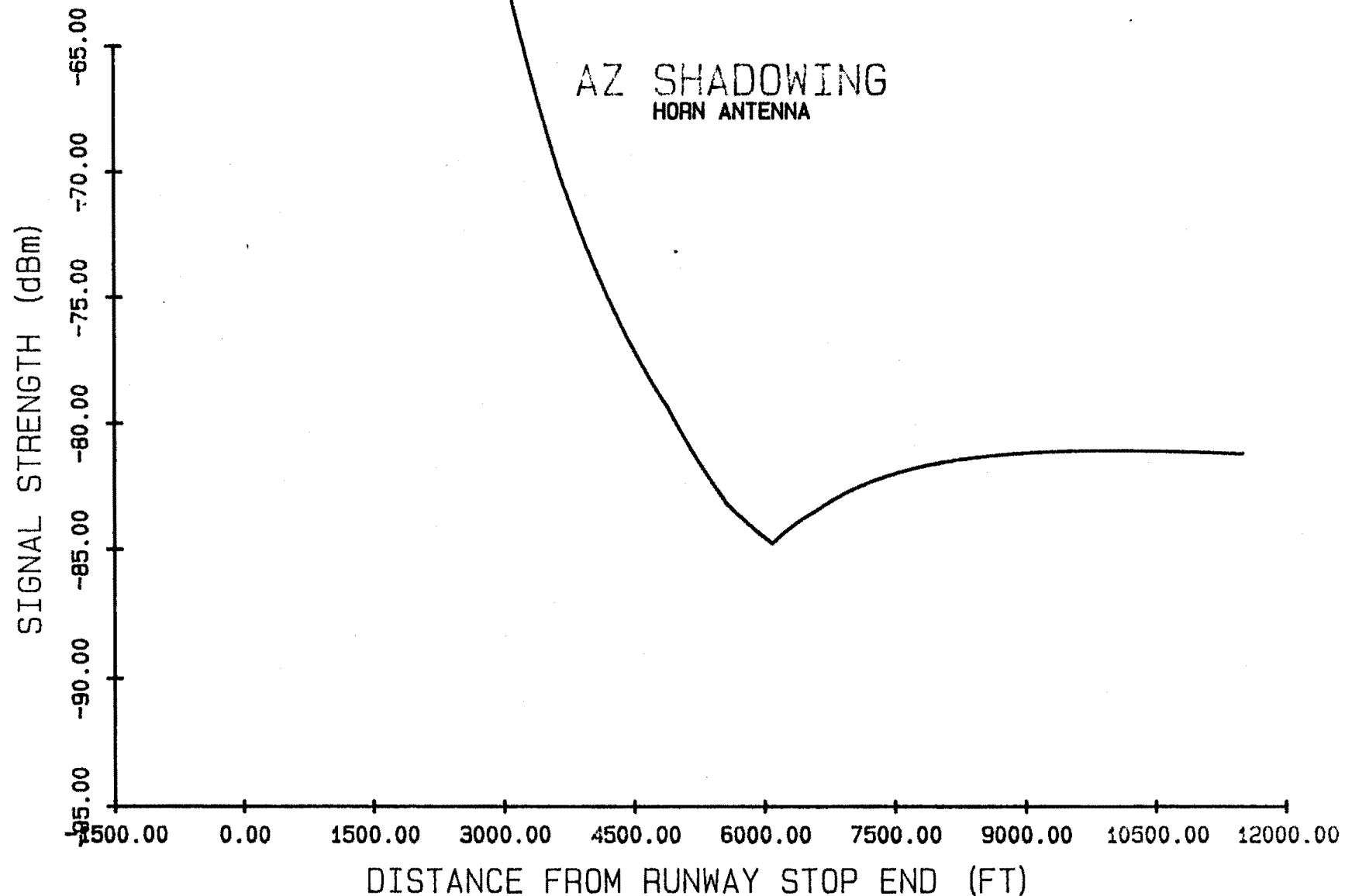


FIGURE 28. SIGNAL STRENGTH 8 FEET ABOVE RUNWAY SURFACE WITH HORN ANTENNA FOR CYLINDER RADIUS OF 177395 FEET AND PHASE CENTER AT 5297.9 FEET.

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MLS MATHEMATICAL MODELING PERFORMED BY:
FAA TECHNICAL CENTER, ACT-140
ATLANTIC CITY AIRPORT, NJ 08405
TITLE: SIGNAL LEVEL 8 FT ABOVE RUNWAY, RADIUS = 177395
RUN #: 5297 DATE: 17-MAR-88 10:33:33
RUNWAY: 17R AIRPORT: DENVER, COLORADO-STAPLETON

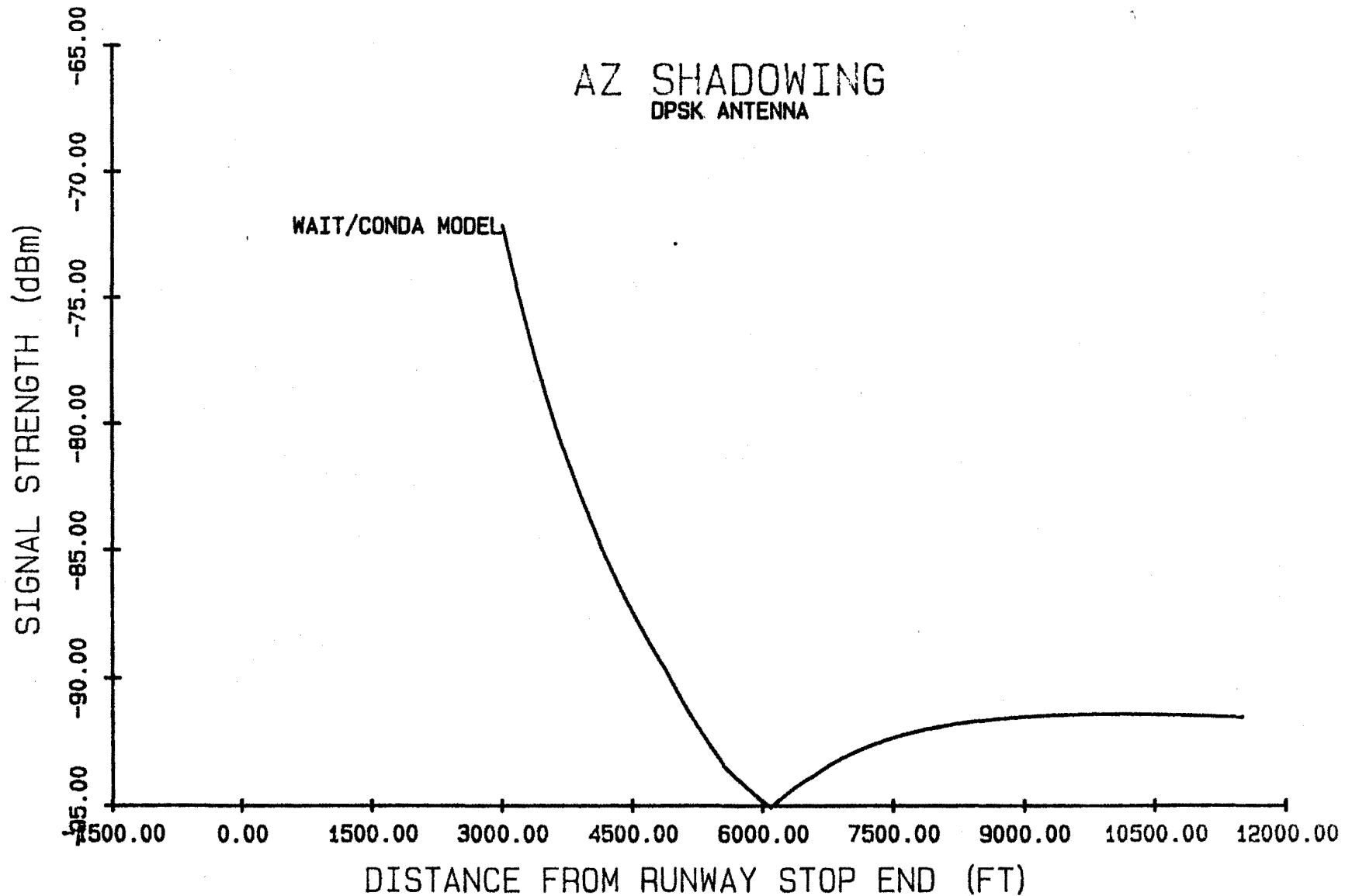


FIGURE 29. SIGNAL STRENGTH 8 FEET ABOVE RUNWAY SURFACE WITH DPSK ANTENNA FOR CYLINDER RADIUS OF 177395 FEET AND PHASE CENTER AT 5297.9 FEET.

03/17/88 10:50:45

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TABLE 1. SUMMARY OF MODEL DATA COMPARISON WITH SIGNAL LEVEL MEASUREMENTS

Transmit Antenna Phase Center Height (ft msl)	Receiver Location (ft)	Comparison Aspect	Fig	Radius = 197,050	Fig	Radius = 273,220	Fig	Radius = 177,395
5,273.0	6,074	Shape	6	similar > 22 ft diverge < 22 ft	13	similar > 30 ft different < 30 ft	20	different slopes
		Level		within 3dB > 15 ft within 8dB < 15 ft		within 4 dB		within 6 dB
	11,500	Shape	7	similar but some divergence	14	similar > 27 ft diverge < 27 ft	21	similar > 25 ft diverge < 25 ft
		Level		within 5dB having bias of 4dB		within 3 dB < 27 ft		within 4 dB
5,270.2	6,074	Shape	8	similar but some divergence	15	similar > 27 ft diverge < 27 ft	22	different slopes
		Level		within 5dB		within 3dB		within 5 dB
	11,500	Shape	9	different particularity < 25 ft	16	similar > 25 ft diverge < 25 ft	23	similar > 25 ft diverge < 25 ft
		Level		within 4dB		within 2 dB > 25 ft		within 3 dB
5,271.2	6,074	Shape	10	similar but some divergence < 20 ft	17	similar > 25 ft diverge < 25 ft	24	similar but slopes different
		Level		within 8 dB		within 2 dB > 25 ft within 4 dB < 25 ft		within 3 dB
	11,500	Shape	11	different from 20 to 38 ft	18	similar > 25 ft diverge < 25 ft	25	same > 25 ft diverge < 25 ft
		Level		within 2 dB		within 2 dB > 25 ft within 6 dB < 25 ft		within 1dB > 25 ft within 4dB < 25 ft

