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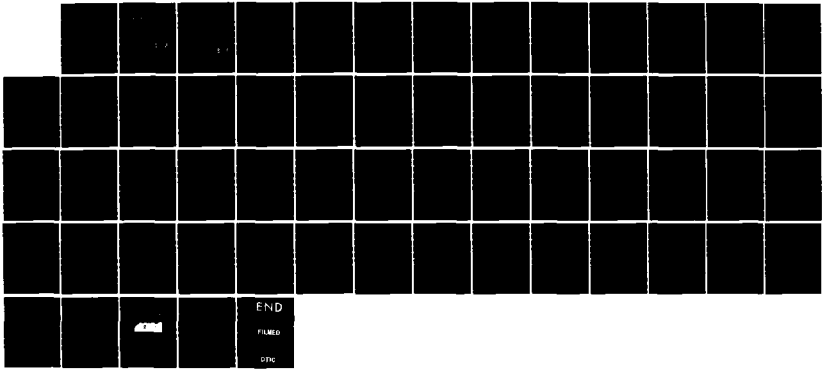

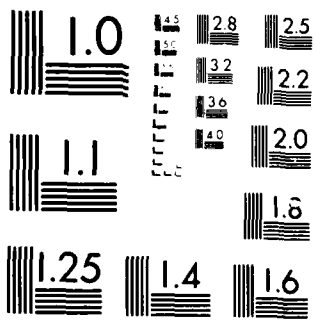

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AN EVALUATION OF THE CAPABILITY OF THE SURFACE CONDITION ANALYZER (SCAN) SENSORS TO MEASURE RUNWAY WATER DEPTH

Calspan Report No. 6857-M-1

by

C.W. Rogers, E.I. Mack and B.I. Wattle

TECHNICAL REPORT

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Final Report
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January 1986

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Field tests of Surface Systems, Inc.'s Surface Condition Analyzer's (SCAN) capability to measure runway water depth during rainfall events were performed at the Spirit of St. Louis Airfield, St. Louis, Mo., during March-May of 1985. These limited tests were scheduled to provide data in real rainfall events and to answer questions of sensor capability relative to true runway water depth and or sensor installation and siting protocol--i.e., should the sensor surface be horizontal or flush relative to a sloping runway surface.

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Field calibration checks showed that sensors installed in the runway surface can measure in-situ water depth in the range 0.030 to 0.40 inches (±0.01 inches). In real rainfall with rates ranging from 0.30 inches/hour (very light) to 6.0 inches/hour (heavy), it was found that the sensor-measured water depth correlated very well with an independently measured water depth over the range 0.03 to 0.10 inches (maximum observed). At the lower end of this range, both sensors measured the same water depth, while at the top end, the sloping, flush-mounted sensor indicated only about 75% of the water depth measured independently and by the horizontally mounted sensor. However, because of surface disruptions produced around the sensors by nonconsistent installation and limitations of the data set, measurement differences could not by wholly attributed to differences in siting protocol of the two sensors. Installation of a full-scale system on an experimental basis on a Navy airfield and further study to define siting protocol and to begin development of algorithms relating water depth to hydroplaning potential are recommended.

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Section 1

INTRODUCTION AND SUMMARY

From 1978 to 1985, under Contracts No. N00014-78-C-0284 and N00014-81-C-0443 with the Office of Naval Research (ONR), Calspan Corporation conducted a limited investigation of the utility of the Surface Condition Analyzer (SCAN)* System sensor in monitoring runway water depth relating to aircraft hydroplaning problems. Sections 2 and 3 of this report describe the Spring 1985 field program and the analysis of the data in relation to the operation of the SCAN sensor in real rainfall events. In addition, Section 1 provides a brief summary of the program, a more extensive background discussion which describes pre-1985 program efforts and results, and Conclusions and Recommendations derived from the 1985 field experiment.

1.1 SUMMARY

Based on a three-year series of laboratory and field tests, it was determined that the 1983-85 version of the SCAN water depth sensor (a disk - shaped object of ~5 inches diameter, implanted in the runway) can measure in-situ water depth in the range 0.03 to 0.40 inches (±0.01 inches). While questions concerning installation protocol and representativeness remain, it is recommended that the new SCAN sensors be considered for use in the operational determination of runway water depth.

*Manufactured by Surface Systems, Inc. (SSI), St. Louis, MO 63144

As of late 1985, a SCAN system for monitoring water depth is not available as an operationally-suitable, off-the-shelf system. Hardware and electronics to operational or mil-spec standards and user-friendly software and CRT displays have not yet been designed. Additionally, questions pertaining to the ultimate utility of water depth measurements, per se, in decision-making relative to runway traction or the hydroplaning potential for various aircraft on various runway surfaces have yet to be answered. However, continued development of the SCAN System and study of water depth vs. traction relationships appear warranted.

1.2 PRE-1985 PROGRAM TESTS AND RESULTS

During FY '78 and '79 for the Naval Air Systems Command (AIR 553) under Contract No. N00014-78-C-0284 with ONR, Calspan conducted an operational research investigation of the feasibility of utilizing the Surface Condition Analyzer System as an indicator of airport runway conditions with respect to icing and/or wet runway hydroplaning situations. That study focused principally on runway ice-detection capability. In response to Calspan's recommendations under that contract and to SSI expectations, the Navy elected to evaluate a full-scale SCAN System for water depth measurement and funded Contract No. N00014-81-C-0443 with Calspan.

Subsequently, in the summer of 1981, Calspan evaluated SSI's original ice detection/water depth concept modified for measuring runway water depth exclusively, investigating a system

(SCAN System-16) consisting of eight sensors installed on a runway at Pensacola Naval Air Station. This investigation showed that this sensor was not suited for water depth measurements because of its sensitivity to water conductivity.

1.2.1. Preliminary Laboratory Evaluation of a New Sensor Concept

During 1982, SSI devised a new sensor based on an entirely different concept (currently considered SSI proprietary)* unaffected by water conductivity. A breadboard version was demonstrated during September 1982. The new sensor concept was tested in Calspan's low speed wind tunnel (Atmospheric Simulation Facility) over a range of wind and rainfall conditions (up to a combination of 20 mph winds and 5 in/hr rain rate) in January 1983.

Subsequent to Calspan's preliminary wind/rain-test evaluation, we recommended that further laboratory testing for effects of potential environmental hazards on sensor performance be accomplished before a complete system was installed at an airfield. Laboratory tests were conducted by Calspan in May 1983 to examine the influence of heating, inclination, dirt loading, water conductivity and abrasion on the performance of the new SCAN sensor.

*SSI's new sensor concept is considered proprietary until patent rights are clarified, and no reference to the physics of the sensor's conceptual design is made or implied in this report.

For the conditions of these limited laboratory tests of a 'developmental' version of the new sensor, our principal conclusions were as follows:

1) The new SCAN sensor accurately measures water layer depths (of 0.1 and 0.2 inches) for a static-parallel surface better than standard manual equipment.

2) The SCAN device can measure peak and trough water depths of waves induced by windshear and heavy rainfall under separate and combined conditions of 20 mph winds and 5 in/hr rainfall. The number of valid signals recorded under these conditions is significantly lower than those recorded under ideal static conditions, but more than sufficient data are provided.

3) Proper installation of the sensor in the runway will be critical, as the sensor is unable to respond to static water at an inclination in excess of one degree or to non-static conditions at angles greater than two degrees.

4) The sensor continues to function adequately under nominal dirt loadings of up to $0.03\ g/cm^2$ on the sensor.

5) Sensor response is unaffected by water conductivity values typical of rain water (up to at least 700 μmho/cm).

6) Abrasion and pitting to depths of 50 microns did not materially affect sensor performance.

7) A potential thermal problem should be addressed.

The tests indicated that the sensor should perform adequately and stand-up under runway conditions of dirt, water conductivity and abrasion. Therefore, we recommended that SSI and the Navy proceed with further development, and testing and evaluation under actual runway conditions at a field site in the St. Louis area, with careful attention to be paid to sensor installation and inclination angle.

1.2.2 Results from Preliminary 1983 Field Trials of the New SCAN Sensor

SSI installed a new sensor in its parking lot to observe its "operational" performance and began constructing required hardware and developing software for a demonstration system to be installed at the Spirit of St. Louis Airport for longer-term observations in an actual runway environment. It was recommended that, as a minimum, a 3-sensor system be installed and that provision be made for wind and rainfall rate measurements. To this end, Calspan purchased a tipping-bucket raingage for use in subsequent field tests.

Suggested objectives of the test program included:

1) Examination of sensor performance in a 'real-world', wet runway environment: e.g.,

- of measurement capability
- documentation of response to actual precipitation events
- representativeness of sensor measurements

- influence of environmental circumstances; i.e., dirt and rubber deposits, aircraft engine noise, etc.

2) Determination of installation requirements; i.e., how critical is level installation of the sensors.

3) Determination of longer-term survivability from effects of:

- diurnal thermal cycling
- landing impacts and vibration
- chemical challenge
- abrasion and scoring

During June and September-October 1983, Calspan conducted an in-situ evaluation of three 'second-generation' SCAN sensors installed in the runway at the Spirit of St. Louis Airport in Chesterfield, MO, at sites selected during a May 1983 inspection. Volumetric in-situ calibration checks showed that the sensors could measure water depth to $\pm$0.01 inches over the depth range 0.03 to 0.40 inches.

During the September field trip, three light rain events occurred. Rainfall rates were typically <0.2 in/hr, and the general runway surface only became wet; at these low rain rates, most of the water resided in and ran through the interstitial areas of the runway aggregate, pooling only in

depressions and seams. When the rainfall rate approached 0.3 inches/hour, we began to see a distinct depth on the flat areas of the runway as the water overflowed the interstitial troughs.

On the basis of manual measurements and visual observations of the three sensors under light rainfall conditions, the flush-mounted, non-level sensor was most representative of the general runway surface. A centerline sensor, (level and below grade) was observed to accumulate a layer of water before either of the other two sensors, helping to indicate the presence of standing water in runway depressions. A third sensor, level and at-grade but on the slope of the runway, always had a thicker layer of water on it than did the surrounding surface. Thus, at the observed low rainfall rates (i.e. <0.3 inches/hr) and non-static conditions, the non-level sensor indications of water depth appeared more representative of runway surface conditions (not puddles) than those from the level, at-grade sensor; while the recessed sensor was more representative of puddles. However independent, quantitative, in situ runway water depth measurements under higher rainfall rates were required in order to fully assess sensor performance and representativeness.

The sensors suffered no known adverse effects from three months summertime environmental exposure, except for a loss of sensitivity due to a thermal stressing problem which has apparently been corrected in later sensor models. The

aluminum surfaces of all sensors were relatively free of pits and scratches. Environmental aging of the epoxy-portion of the sensor surface appeared to promote its wettability and, thus, water-flow characteristics.

In an interim report (Mack, 1984), which summarized the entire program to date and provided details of the 1983 field effort, Calspan concluded that sensor performance in actual heavy rainfall and running-water events remained undocumented. It was recommended that SSI demonstrate a fully functional advanced version of a four-sensor system at Spirit prior to installation of such a system at Pensacola. The anticipated system was to incorporate software and hardware with an upgraded version of the sensor in a package suitable for transfer and installation at a Naval airfield. Data from tests of this system at Spirit would be used to examine the following basic questions:

1. Can the new sensor reliably determine runway water depth?
2. What is sensor siting protocol? Is this airfield specific?
3. Can water depth be measured representatively on a runway with as few as 5 to 10 spot measurements?

A portion of the recommended system became ready in late Winter of 1985, and was installed at Spirit in preparation for the Spring rain season. Results and analyses of data from the ensuing field program are presented in the body of this report.

1.3 SUMMARY AND CONCLUSIONS FROM THE 1985 FIELD PROGRAM

The 1985 field program at Spirit of St. Louis Airport extended from early March through May. Two new SCAN sensors were installed within ~1.5 ft. of each other in the center of a 70 x 70 ft. grid painted on the runway at the 1983 runway site. (Details of experimental procedures are provided in Section 2.) Sensor-1(S1) was installed flush with the runway surface at an inclination of 1° 25' and Sensor-2(S2) was installed horizontally, i.e., virtually level with a measured inclination of 0° 6'. After installation, Calspan verified the calibration of both sensors using the volumetric technique developed earlier. In 10 natural rainfall episodes, Calspan acquired independent, runway water depth measurements for comparison with the SCAN measured runway water depths. Subsequently, during April and May, the SCAN system alone acquired data in six rainfall events, which, with the observations from the Calspan measurement periods, provided a program total of approximately 600 sets of S1 and S2 measurements. These data and statistical analyses are discussed in detail in Section 3.

1.3.1. Conclusions Derived from the 1985 Field Experiment

Based on the calibration checks, comparison of Calspan measured water depths and SCAN-measured water depths, and a statistical analysis of the SCAN data set, we arrived at the following conclusions:

1. Both sensors accurately measured static water depth (to $\pm$0.01 inch) for calibration water depths ranging from at least 0.05 to 0.35 inches, confirming the calibration checks of the 1983 sensors.

2. Within the limitations and constraints of the independent, manual water depth measurements, the SCAN sensor is capable of accurately measuring the water depth occurring over the sensor during real rainfall events. For light, intermittent rainfall rates (i.e., $\leq$0.3 in/hr) which appeared to produce static, quasi-steady runway water depths of $\sim$0.030 inches, both sensors measured this depth within the resolution of the system. For heavy rainfall rates, $\geq$0.5 in/hr and corresponding free-flowing water depths of 0.04 to 0.09 inches, Sensor 2 (level) measured the true water depth; for these conditions, the S2 depth was larger than the Sensor 1 (flush, inclined) depth with reported differences of 0.01 to 0.02 inches. These water depth differences may or may not be important in defining hydroplaning regimes based on water depth ranges. Several observations at water depths above 0.10 inches showed no difference in depths measured by the two sensors.

3. The difference in water depths measured at the two sensors cannot be interpreted as resulting entirely from the difference in orientation of the surfaces of the two sensors. Runway surface disruptions which were produced during sensor installation may have produced artifical drainage away from Sensor 1 and thus contributed to the difference in water depth

between the two sensors. Hence we cannot draw conclusions relative to flush vs. horizontal sensor installation.

4. Of the two methods used by SSI for computing water depth during these tests, single channel rounded and weighted mean, the weighted mean appeared to provide the more accurate determination of runway water depth.

5. In connection with SSI's indicated lower limits of detection, 0.015 inches for S2 and 0.03 inches for S1, our analyses showed that S1 reported larger water depth than S2 at true water depths of ~0.015 inches. Examination of a number of these occurrences showed that Sensor 1 had acquired water depths for only a very small fraction of the possible number of observations. Consequently, we suggest determining and setting a threshold percentage of observations below which sensor detected water depth would not be reported.

1.3.2. Recommendations

As a result of our study of the SCAN sensors we make the following recommendations:

1. The SCAN sensors can adequately measure water depth in the range 0.03 to 0.40 inches in nearly realtime, and we recommend the SCAN sensors be considered for use in operational determination of runway water depth pending further development and testing outlined below.

2. Additional data should be acquired in real rainfall events in real-world runway scenarios to answer questions concerning flush vs. horizontal installation and representativeness.

3. In any future study, the sensors should be carefully installed with a minimum of runway surface disruption to insure the presence of characteristic runway material and surface abutting the edge (for 360°) of the large epoxy mass used for the sensor installation.

4. For any future studies, the raingauge should be located in the immediate vicinity of the sensors' runway installation in order to better correlate sensor response to rainfall rates.

5. Finally, a 'full-scale' system, installed on an experimental basis, as for items 1-4 above, on a Navy airfield could begin to provide data for development of algorithms relating water depth to hydroplaning potential for various Navy aircraft.

SECTION 2

EXPERIMENTAL PROCEDURE

2.1 1983 EXPERIMENT

During May 1983, three sites were selected for installation of SCAN sensors in the runway at the Spirit of St. Louis Airport in Chesterfield, MO. Three sensors, originally designated 3-1, 3-2 and 4-1, were located approximately 1000 feet from the west end of runway 07-25. Sensor 3-1 was located near the centerline, 73.5 feet from the south edge of the runway and was mounted level but about 2 millimeters below grade. Sensor 3-2 was 43 feet 2 inches from the runway's south edge and was flush mounted (maximum inclination of 1° 40'). Sensor 4-1 was also located 43 feet 2 inches from the runway edge but was 1 foot 8 inches closer to the west end of the runway; it was mounted level but at grade.

Baseline calibrations were performed on all sensors by placing a ring of diameter 7.3 cm on the sensor surface, sealing it with rope caulk, and then filling the ring with known volumes of water measured from a graduated burette (held in a ring stand above the sensor) to obtain the desired calibration water depths. Each depth was recorded over a period of time (usually two to four minutes) in order to accumulate sufficient data. Calibrations were performed only for S-1 in June 1983 and for all sensors in the Fall of 1983.

The calibration data (Figure 1) show that for near static conditions the sensors accurately measured water depth over the range 0.03-0.40 inches. Sensor 3-2 was an exception at depths below 0.1 inches, and its inability to measure correctly at low depth values may have been related to the problem of the sloping sensor surface as noted in the laboratory. Note that the calibration of Sensor 3-1 did not change between the June and September data.

For the Spring 1985 experimental period, old Sensors 3-2 and 4-1 were removed and replaced with modified sensors. New Sensor-1(S1) was installed at the old 4-1 site and was mounted flush with the runway surface at an angle to the horizontal of $1^{\circ}25'$. New Sensor-2(S2) was installed approximately horizontal (0 6') at the old 3-2 site. These sensors were calibrated in the manner previously used, and the results are shown in Figure 2. As before, the sensors correctly measured the depth of a static water layer covering the sensor, which for this calibration covered the water depth range, 0.05 to 0.35 inches.

In the Fall of 1983 we painted a grid of sampling points (see Figure 3) over an area of ~5000 ft on the runway so that in-rain water depth measurements could be repeated at certain fixed locations using a hand-held NASA water depth gauge. In addition, the tipping-bucket raingauge was installed approximately 800 feet to the southeast of the sensors (Figure 4).

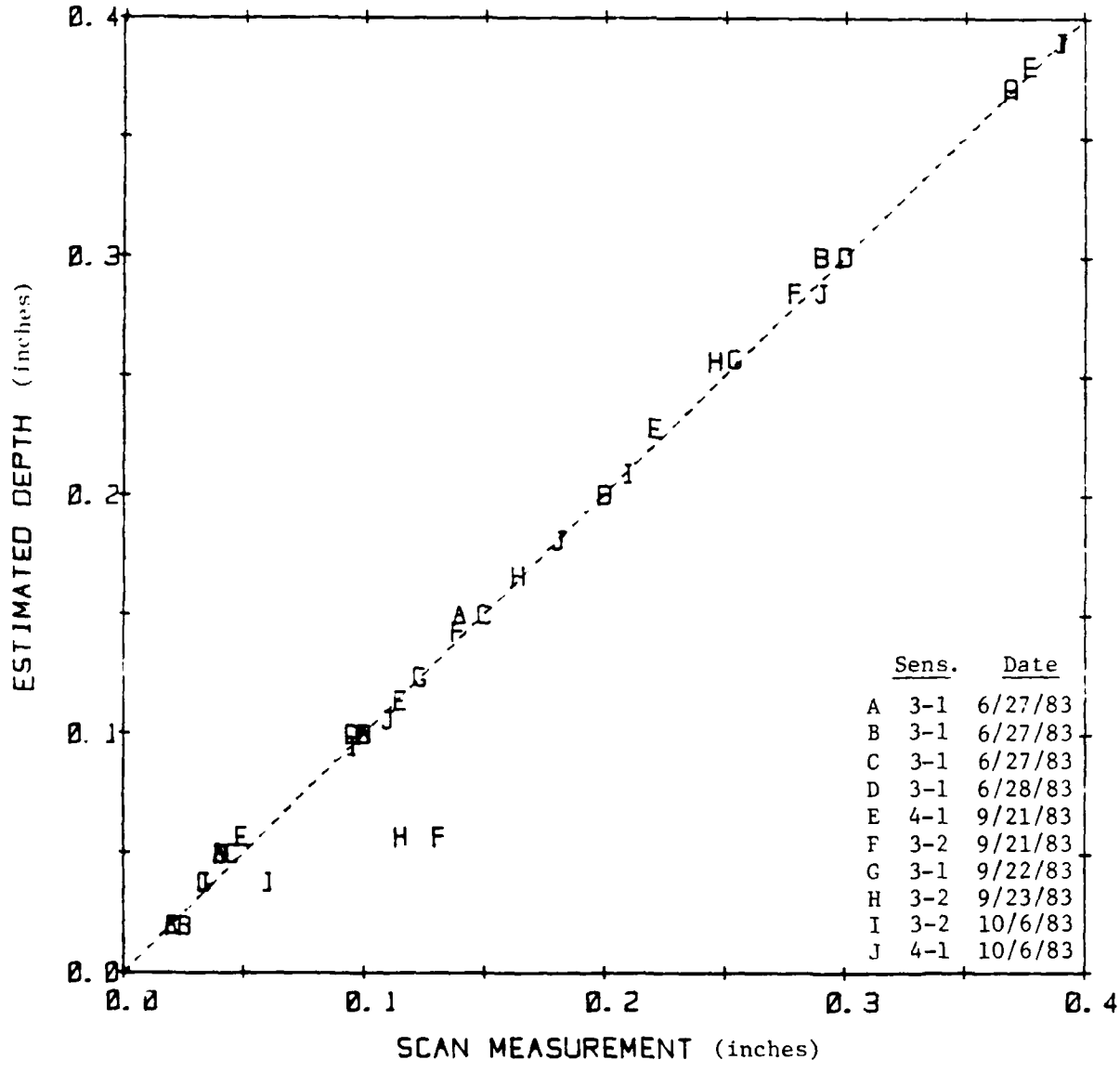

Figure 1

CALIBRATION RESULTS OF THE THREE SCAN WATER DEPTH SENSORS AFTER INSTALLATION AT SPIRIT OF ST. LOUIS AIRPORT.

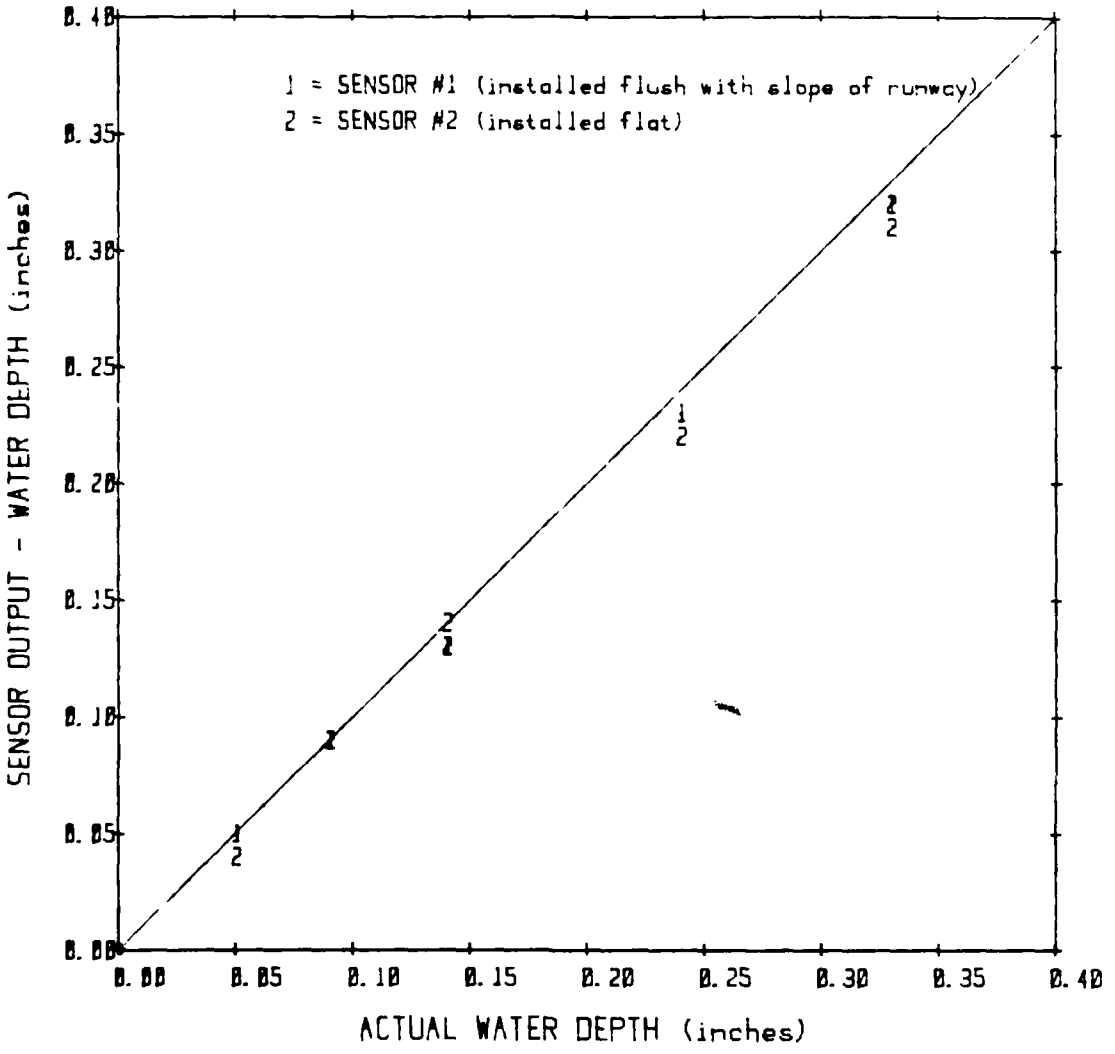

Figure 2

CALIBRATION CHECK: SENSOR OUTPUT vs. ACTUAL WATER DEPTH, 3/26/85

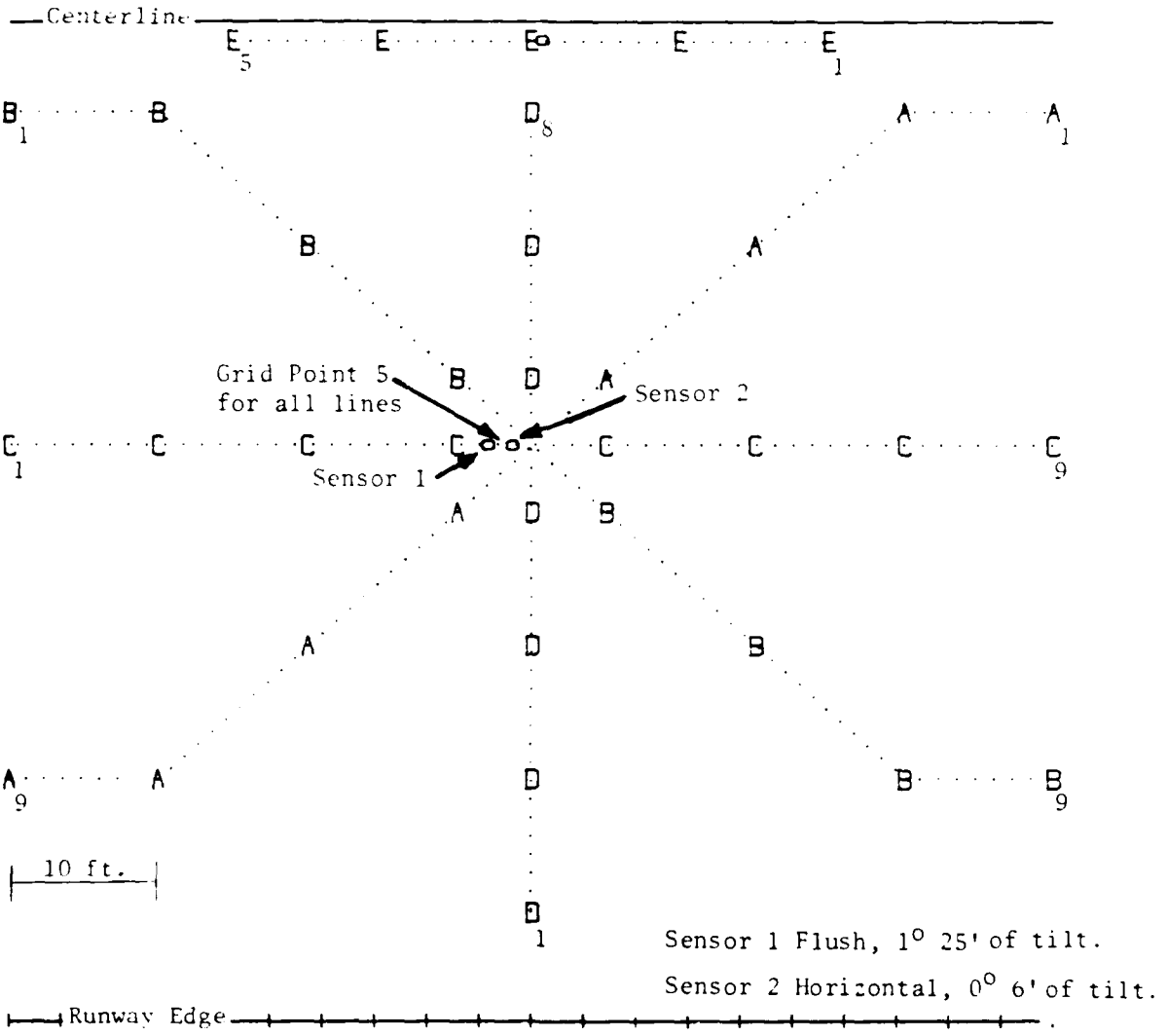

Figure 3

LINES A-E DEFINING THE MEASUREMENT GRID IN THE VICINITY OF TWO SCAN WATER DEPTH SENSORS MOUNTED AT SPIRIT OF ST. LOUIS AIRPORT, RUNWAY 07.

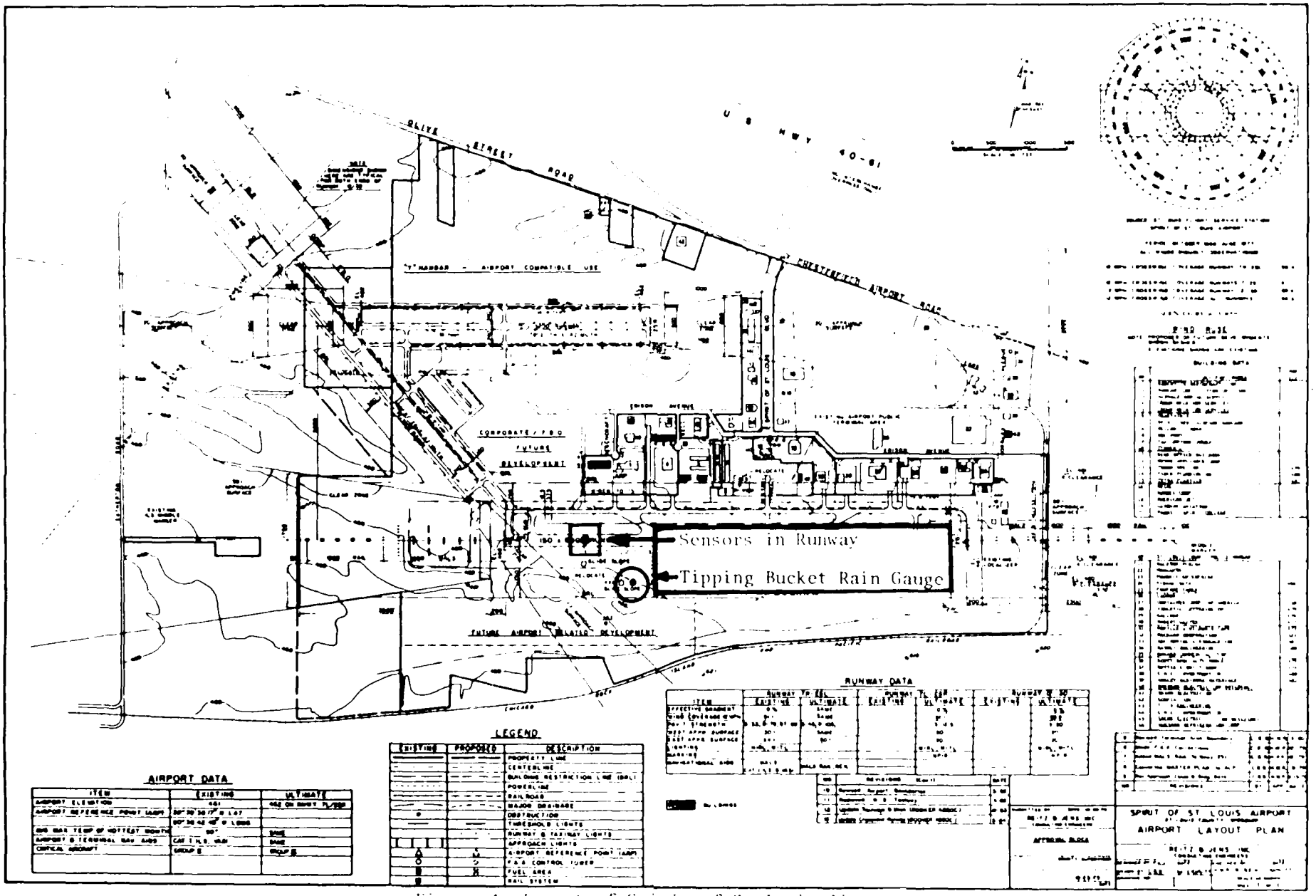

Figure 1 Layout of Spirit of St Louis Airport

2.2 1985 EXPERIMENT

The SCAN sensor system software provided measurements every two minutes. Among the data provided were two-minute mean water depths from each sensor, the number of 0.01-inch increments of rainfall (number of tips of the 0.01 inch bucket) occurring during the two minutes, wind velocity, temperature of the air and of each sensor surface, and relative humidity.

Two water depths were reported for each sensor. One was obtained by computing the depth only from the channel with the highest number of recorded counts, and rounding the value to the nearest hundredth of an inch. The other water depth was obtained by computing a weighted mean from channel counts times channel depth. This water depth value was labeled "average" and was reported to a thousandth of an inch.

2.2.1. Calspan Measured Water Depth

The independent runway water depths measured at the grid points shown in Figure 3 were acquired with the hand-held NASA water depth gauge. This gauge measures in quantum steps of 0.02 inches, starting at 0.02 inches as the first non-zero value. Thus the gauge measures no water depth when it could actually be as large as 0.019 inches, measures 0.02 inches when the depth is between 0.02 and 0.039 inches, etc. The range of actual water depth associated with the manually measured depths should be kept in mind during the succeeding discussions, especially when

these Calspan water depths are compared to the greater-resolution data from the SCAN sensors.

Calspan employed two measurement protocols in determining runway water depth, a grid procedure and series procedure. Under the grid protocol, measurements were taken at the grid points shown in Figure 3. The grid was traversed by moving in the grid line sequence D,A,C, and B, with the first three lines travelled in ascending grid number sequence and the last in descending sequence. The time required to obtain measurements over the grid was of the order of two to three minutes. For each grid line, Point 5 was located midway between the two scan sensors.

The series measurement approach consisted of acquiring measurements only at Point 5 at 5 to 15 second intervals over a two minute period for comparison with the water depths measured by the SCAN sensors during a two minute period.

The hand-held manually-operated depth gauge was the only independent measure of water depth available to us for use in rain events. (Volumetric calibrations independently demonstrated accuracy of the SCAN sensors in measurement of water depth actually over the sensor). Hence, we operate on the premise that the on-runway measurements of water depth with the gauge are accurate to the resolution of the depth ranges and represent 'true' runway water depth, particularly in the area between the two SCAN sensors.

2.2.2 Description of Data Set

Calspan and SCAN measurements were acquired jointly on 29 and 30 March 1985. The 29th included both a morning rainfall event maximum of 1.2 inches/hr. over two minutes during which the maximum average Calspan water depth reached 0.09 in, and an afternoon event of maximum 0.90 in/hr (two minutes) during which the maximum average Calspan water depth approached 0.04 inches. On the 30th, a one-hour stretch of rainfall occurred in early evening during which the maximum was 0.6 in/hr and the maximum average Calspan depth again approached 0.04 in.

For each data set containing contemporary Calspan and SCAN sensor water depth measuremnts, the time history of each Calspan Point 5 measurement sequence (either grid or series) was tabulated. The Calspan data were then blocked-off into two-minute periods which matched the data acquisition period of the SCAN system. Appropriate two minute average values of the Calspan data were computed for comparison with the SCAN data. For the series type Calspan measurements, the average was the arithmetic mean of the Calspan values acquired during the two minute sampling period. For grid type measurements, the average was a mean weighted by the fraction of the two-minute SCAN period for which the Point 5 spot measurement was representative.

2.2.3. Specification of Representative Rainfall Rate

During the September 1983 field trip and the Spring 1985 field trip it was qualitatively observed that for rainfall

rates typically <0.2 in/hr the general runway surface only became wet as most of the water resided in and ran through the interstitial areas of the runway aggregate, pooling only in depressions and seams. When the rainfall rate approached 0.3 in/hr we began to see a distinct depth on the flat areas of the runway as the water overflowed the intersitial troughs. These observations supported our intuitive considerations that water depth on a runway should be dependent both on drainage and, with some time lag, on rainfall intensity and duration. In view of the lag and storage aspects, we decided to use total rainfall over some time period greater than two minutes to characterize the various rainfall events and for comparison with runway water depth measurements.

To determine an appropriate time period, we plotted time histories of two-minute water depths from S1 and S2 versus total rainfall over time periods ranging from two to ten minutes, with all the time periods terminating at the ending time of the two minute period over which the SCAN data were acquired. Examination revealed that total rainfall over six (6) minutes best correlated with the Calspan and SCAN runway water depths, both in intensity and fluctuation. Therefore, throughout this report the measured rainfall over six minutes is used to characterize individual rainfall events and their time histories.

SECTION 3

RESULTS

3.1 HOW WELL DO SCAN SENSORS MEASURE RUNWAY WATER DEPTH IN REAL RAINFALL EVENTS?

A main question which was to be examined by the 1985 field experiment was how well does the SCAN sensor measure runway water depth in real rainfall events. To answer this question we computed average Calspan measured runway water depths (as described in Section 2.2.1) for ten data sets and arranged them in descending order of water depth. These data are shown in Table 1 along with the S2 and S1 values of runway water depth, the six-minute rainfall and the type of Calspan measurement protocol employed.

The Calspan runway water depths range from a maximum of 0.09 inches to a minimum of 0.02 inches (average values of 0.02 inches which arise from all data points in the set being 0.02 in value are presented as 0.02-.039 inches because of the quantum measuring restriction of the hand-held NASA gauge). From the table we see that S2 essentially measures the runway water depth except for the maximum Calspan value, for which the S2 value is only 80% of the Calspan value. Compared to S2, S1 on the other hand consistently reports lower water depths for the five largest water depths. At the smaller five S2 values, the difference between S2 and S1 decreases as the S2 value becomes smaller, until the two sensors essentially measure the same depth at the shallowest depth measured by S2 (0.028 inches). The

Calspan Water Depth (inches)	S2 (inches)	S1 (inches)	Six-Minute Rainfall (inches)	Calspan Observational Protocol
.09	.070	.048	.09	Grid
.07	.066	.042	.09	Grid
.047	.048	.029	.06	Series
.038	.044	.027	.035	Series
.038	.044	.029	.05	Grid
.02-.039	.040	.028	.05	Grid
.02-.039	.038	.026	.06	Grid
.02-.039	.037	.030	.05	Series
.02-.039	.034	.027	.01	Series
.02-.039	.028	.025	.01	Series

Table 1 Comparison of Calspan Independent Runway Water Depth Measurements and SCAN Sensor Water Depth Measurements.

behavior of S1 depth relative to S2 depth, in terms of the difference in siting and exposure of the two sensors, is examined through a statistical study of the 1985 field data in a subsequent subsection. However, before proceeding to that analysis we present a few time histories of rainfall events to illustrate the SCAN sensors behavior in, and response to, various rainfall intensities and durations.

3.2 TIME HISTORY OF SCAN MEASUREMENTS DURING A SELECTED 1985 RAINFALL EVENT

Figure 5 shows a time history of Sensor 1 water depth, Sensor 2 water depth and six-minute rainfall for the time period during which the maximum depth of 0.07 inches reported for S2 in Table 1 occurred. Both SCAN water depths peak when the six-minute rainfall peaks; as well, both essentially increase and decrease in phase with the rainfall. To show detail, a portion of the data are presented in Figure 6 on an expanded time scale. In addition, Calspan, Grid Point 5 measurements which were taken during this interval are included and plotted at the midpoint of the quantum step, i.e., 0.04-0.059 inch measurement plotted as 0.05 inch. At the three earliest SCAN observation times, all three water depths are near 0.03 inches. Then, as the rainfall rises to its peak at 09:34:30, all three water depths increase more or less in parallel with the Calspan values being the largest and the S1 values being the smallest.

After the rainfall peak, the next set of Calspan measured water depths was acquired in the series mode at five

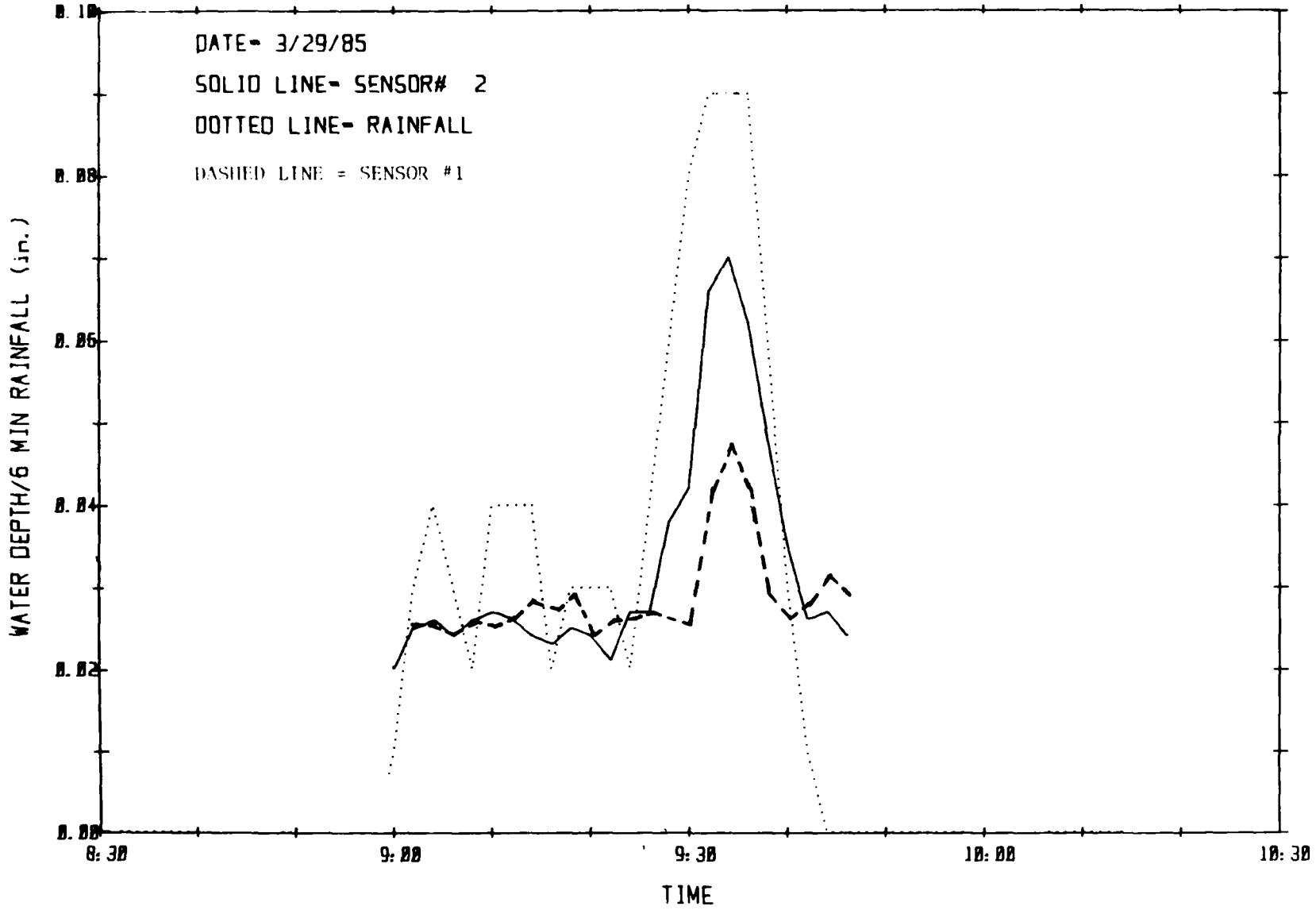

FIGURE 5 Six-minute rainfall and SCAN sensor water depths for a peak rainfall event, 29 March 1985.

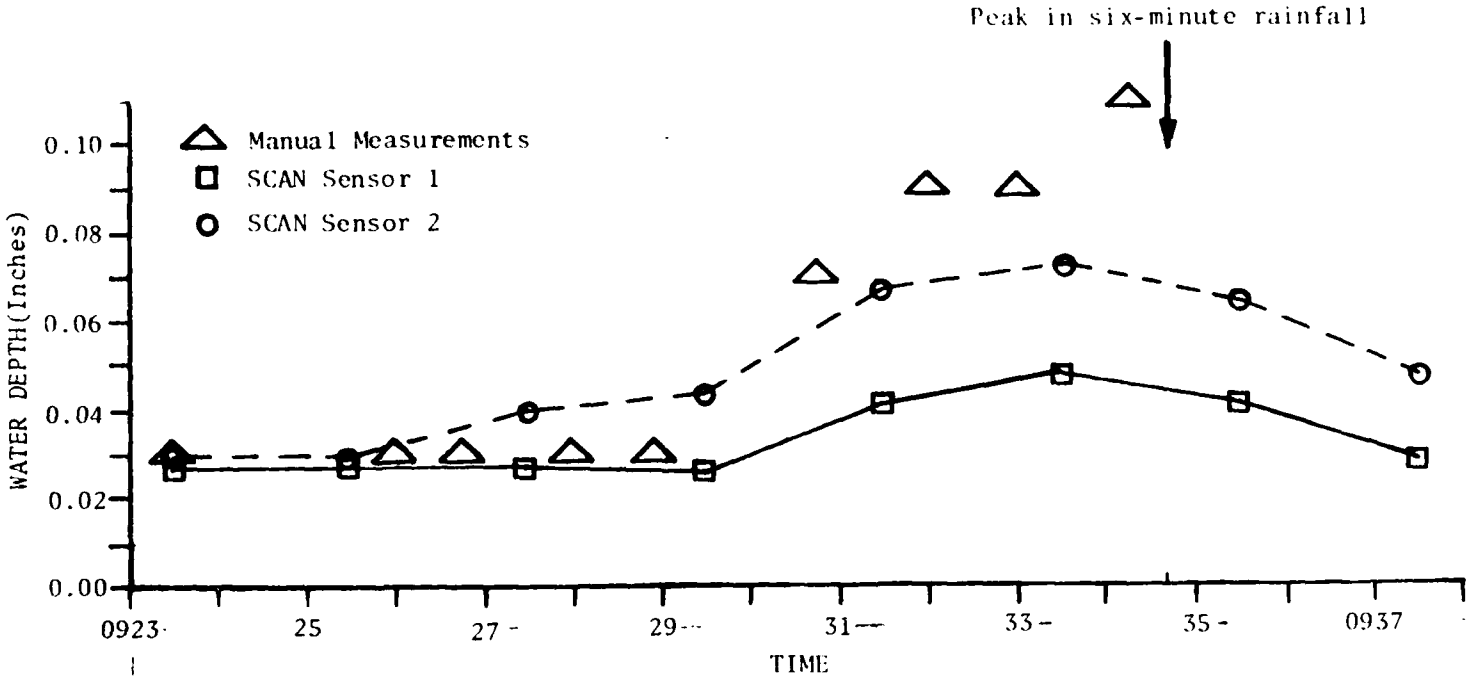

FIGURE 6 Manual, independent runway water depths and SCAN sensor water depths centered around the peak rainfall in FIGURE 5, 29 March 1985.

second intervals. These measurements are best compared to SCAN measurements by further expanding the time scale. In Figure 7 the Calspan data present all the individual measurements, while the horizontal bars with arrows locate the SCAN water depths and show the two-minute period for which the SCAN measurements represent averages.

Although the first six Calspan measurements cover only the last 30 seconds of the first SCAN observation period, the S2 water depth still is compatible with the lower Calspan values. However the S1 value is definitely lower than the Calspan value. The remaining 1.5 minutes of the Calpan data cover 3/4's of the second SCAN observation period. For this period, S2 matches eight of the fifteen observations. Again the S1 value is definitely lower than the Calspan value. These data suggest that S2 measured the true water depth, while S1 measured something lower.

Since the SCAN measurements are weighted means from the distribution of depths measured during the two-minute period, we compared these distributions to the "distributions" of Calspan measurements for the same time period. Figure 8 shows the distributions of water depth measurements from the three sensors. Both the S2 and Calspan curves are peaked near 0.05 inches. The S2 distribution is very similar to the Calspan distribution, remarkable considering that S2 had an enormously large number of observations while Calspan had 15. The S1 distribution on the other hand is peaked at the smaller water depth value of 0.02

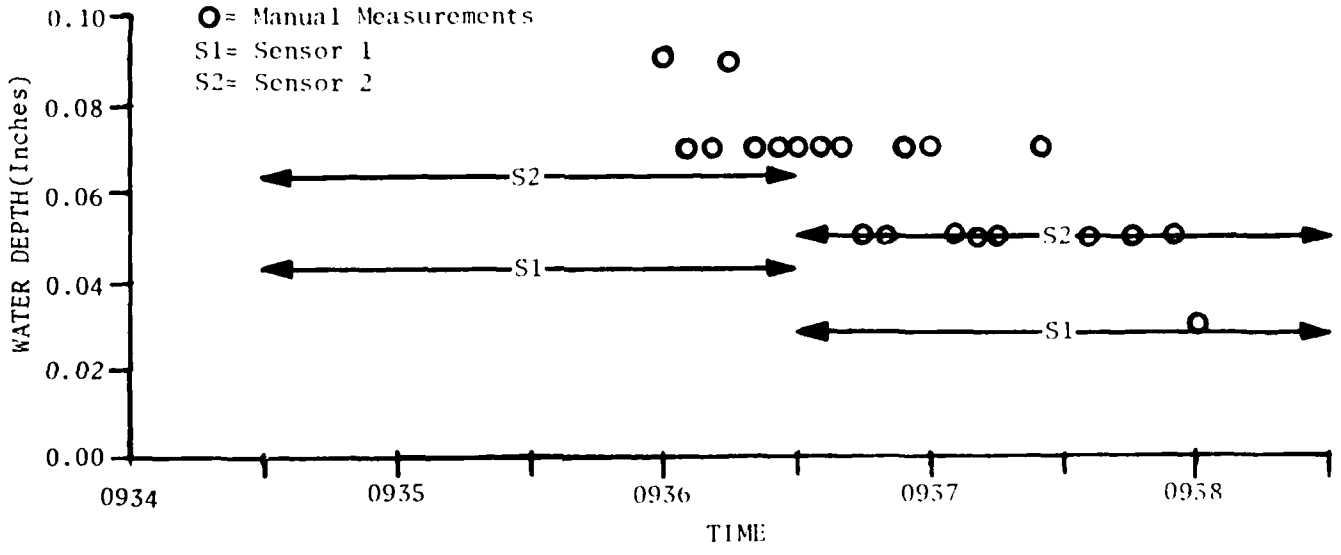

FIGURE 7 Time history comparison of individual, manual water depth measurements with SCAN two-minute averages after peak rainfall in Figure 5.

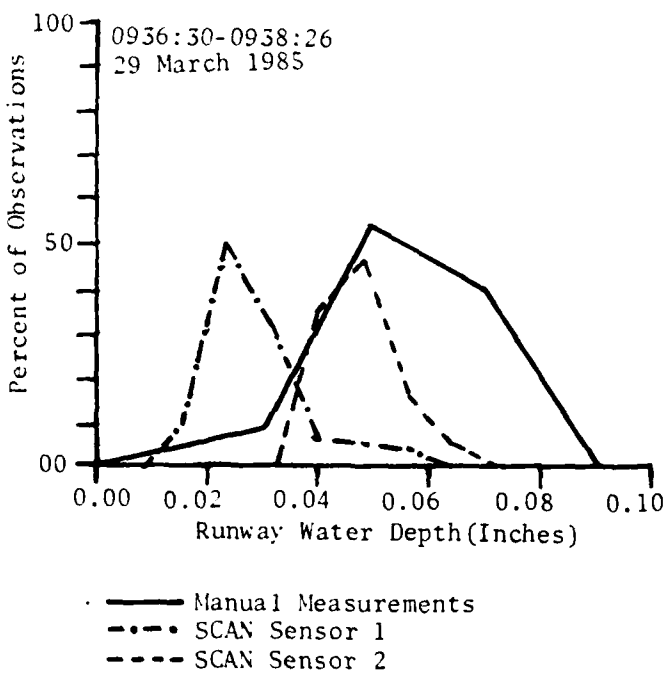

FIGURE 8 Distribution of runway water depth measurements from SCAN and manual sensors after rainfall peak at 0935, 29 March 1985.

inches. Thus, the distributions also support the finding that S2 reported a depth more representative of water depth on the runway between the sensors, while S1 measured something less.

As pointed out in the discussion of Table 1 and of Figures 5 and 6, for water depth values ≤ 0.03 inches the two sensors measure approximately the same water depth. A Calspan set of series measurements was taken at these low water depths later on 29 March at 13:46:26 and are shown in Figure 9a. All three curves are narrow and are peaked between 0.02 and 0.03 inches. Another example from the morning set of observations is shown in Figure 9b. In this set, the Calspan observations are from various grid points sampled during the two minute SCAN observations period. In this case, the two SCAN distributions are almost identical and match the Calspan observations peaked around 0.02 inches.

For both the above cases, six-minute rainfall was in the 0.02-0.04 inches range. These results suggest that for these rainfall rates, the runway water depth reaches a quasi-steady, perhaps static, depth of 0.020-0.030 inches which both sensors detect equally well. However when the rainfall rate rises above 0.04 inches, and appears to become free flowing, then S1 measures a lower water depth than S2. To investigate whether this difference can be interpreted in terms of the different siting of the two sensors, flush for S1 and horizontal for S2, we performed a statistical analysis on the data set which covered the spring rainfall season from 27 March to 27 May 1985.

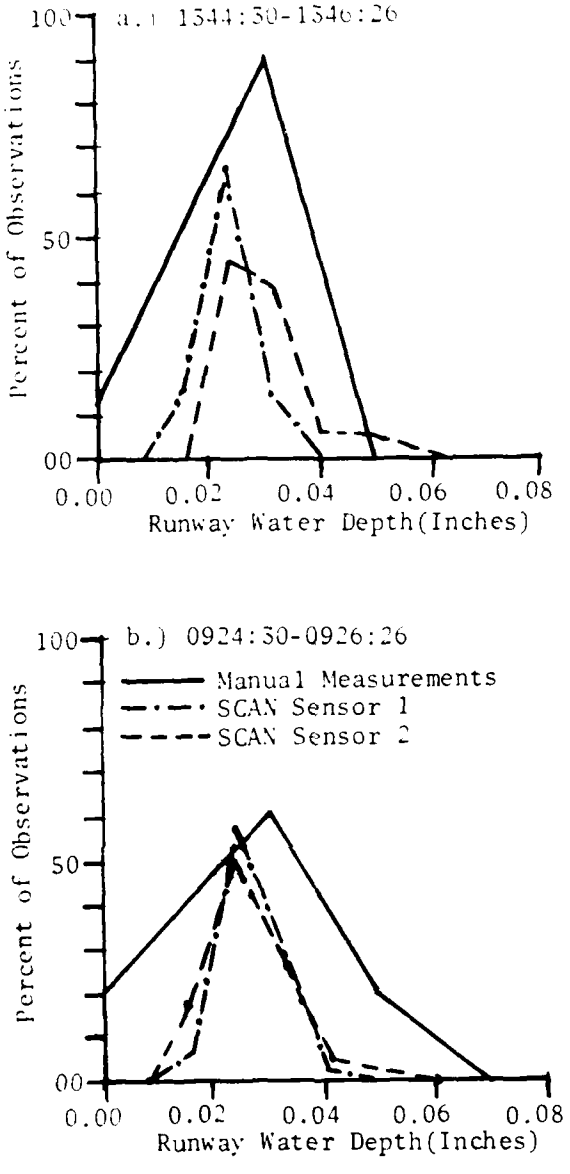

FIGURE 9 Distribution of runway water depth measurements from SCAN and manual sensors for small water depths occurring at start of rainfall events, 29 March 1985.

3.3 STATISTICAL ANALYSIS

The purpose of the statistical analysis was to examine the difference between the S2 and S1 water depths from the complete data set with the aim of examining whether the difference in water depth could be interpreted in terms of a siting difference between the two sensors. The analysis (in Section 3.2) of data from the Calspan measurement period indicated that the difference, Sensor 2 depth minus Sensor 1 depth (S2-S1), was positive for the large depths ($\geq$0.03 in.) and large six-minute rainfall rates ($\geq$0.05 in/6 min); also at small runway water depths (<0.03 in), the sensors measured essentially the same depth. By the statistical study, we show that large values of S2-S1 represent a different sample, and therefore different physical regime, from the standard Gaussian curve associated with random measurement errors. The set of S2-S1 values is stratified by parameters chosen to represent true water depth, designed to show that large positive values of S2-S1 are associated with large runway water depths.

The rainfall events of the 1985 spring season at Spirit of St. Louis Airport for which SCAN data were available are listed in Table 2. These events produced ~600 values of S2-S1 water depth differentials, whose distribution is shown in Figure 10. The percentages plotted are per 0.003 inch interval of S2-S1, centered on $\pm$0.000 in., $\pm$0.003 in., etc. The distribution appears to be basically Gaussian with 77% of the observations lying between $\pm$0.009 in., a value which is

TABLE 2

1985 SCAN FIELD EXPERIMENT RAINFALL EVENTS

DATE	LOCAL TIME	MAXIMUM RAINFALL RATE
3/27/85	02:00-03:00	0.9 inches/hr.
3/29/85	08:00-11:00	1.05 inches/hr.
3/29/85	13:00-15:30	0.8 inches/hr.
3/30/84	18:50-19:10	0.4 inches/hr.
4/05/85	06:40-07:40	1.5 inches/hr.
4/22-23/85	15:30-18:00	2.1 inches/hr.
	20:00-24:00	1.2 inches/hr.
5/1/85	00:00-02:00	6.0 inches/hr.
5/13/85	07:00-11:00	3.0 inches/hr.
5/27/85	16:30-17:00	7.2 inches/hr.

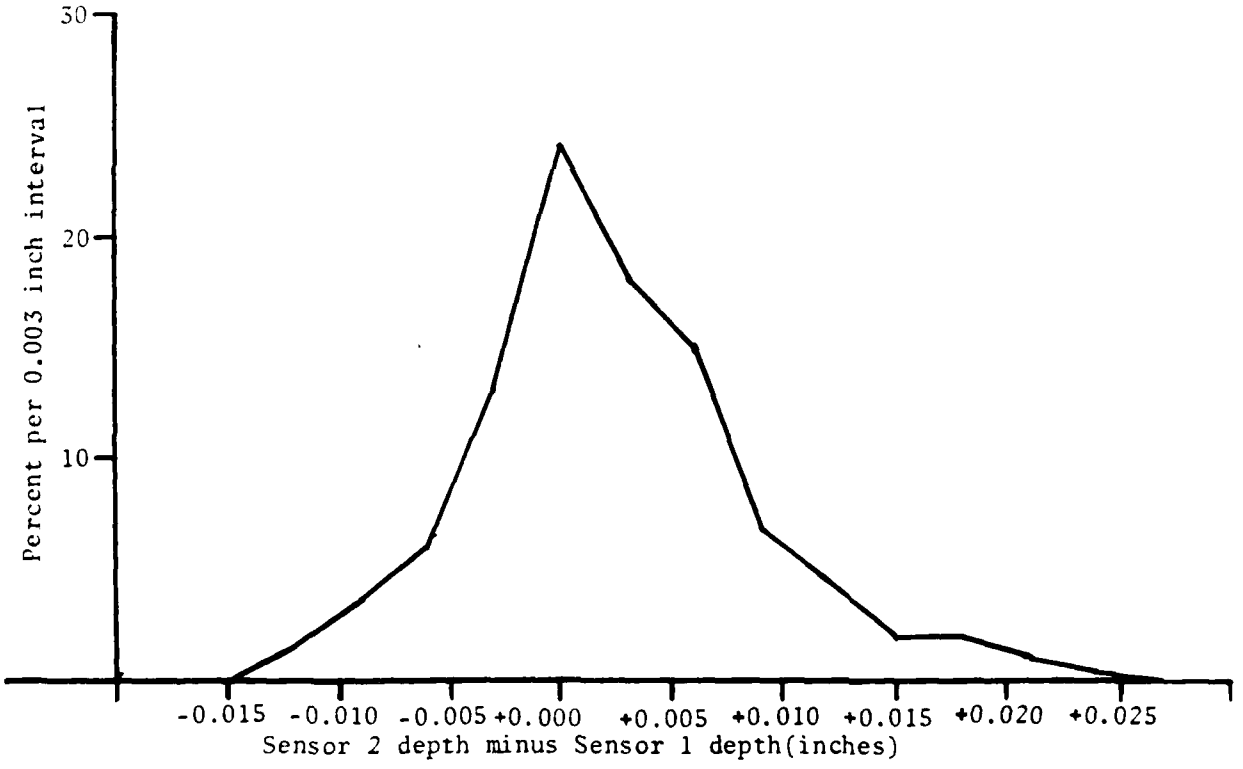

FIGURE 10 Distribution of difference between Sensor 2 water depth and Sensor 1 water depth for Spring 1985 field program.

approximately the water depth resolution of the sensors. However, the positive values of S2-S1 tend to have slightly higher percentages than their negative counterparts, and non-zero percentages extend to larger positive than negative S2-S1 values, as verified by the cumulative percentage from negative to zero being only 37%. Thus, the total distribution shows a basic random distribution of S2-S1 differences, but it also indicates a tendency for more positive than negative values of S2-S1, particularly at the larger magnitudes.

SSI indicated that the S1 measured water depths at and below 0.030 inches were erroneously too high by a factor of two. This error provides smaller S2-S1 which is opposite to the trend suggested by Figure 10. In addition, if we assume S2 measures the true water depth, our statistical data set did not contain any S2 measured depths which were less than 0.015 in., and therefore any erroneous S1 values at and slightly below 0.030 in.

There are a number of measurements in the S2 range, 0.015 to 0.030 inches, for which S1 equals S2, indicating that under some circumstances S1 appeared to operate properly at these depths. These observations seem to come from thin water depths which occur after the institial spaces of the runway are filled and as the water depth decreases following a peak in rainfall. For S2 depths at the lower end of this range which occur at the

beginning of rainfall events, before the interstitial spaces are filled with water, it appears the problem indicated by SSI is present and S1>S2.

The case studies analyzed and presented in Table 1 and Section 3.2 showed that the largest differences between S2 and S1 water depths tended to be associated with large rainfall rates, an independent, albeit secondary, measure of runway water depth. Consequently we divided the complete sample into two data sets (based on information in Table 1 and examination of case studies), one set with six minute rainfall <0.03 in and the other $\geq$0.03 in. The resulting distributions are shown in Figure 11. Basically, the distributions appear Gaussian, although the data set for the higher rainfall rate has larger percentages at the bigger positive values of S2-S1.

An apparent reason for less discrimination by rainfall rate probably lies in the 800 foot separation between rain gauge and runway sensor location. Many of the rainfall events in the entire data sample were characterized by showers, and therefore it is possible for relatively large rainfall rates to have occurred at the rain gauge but not at the sensor site, even when six-minute total rainfall is used as the measure of rainfall intensity. This result suggested that we would have to use a non-independent measure for separating out high rainfall and large water depth events at the sensors, namely the water depth measured by Sensor 2 itself.

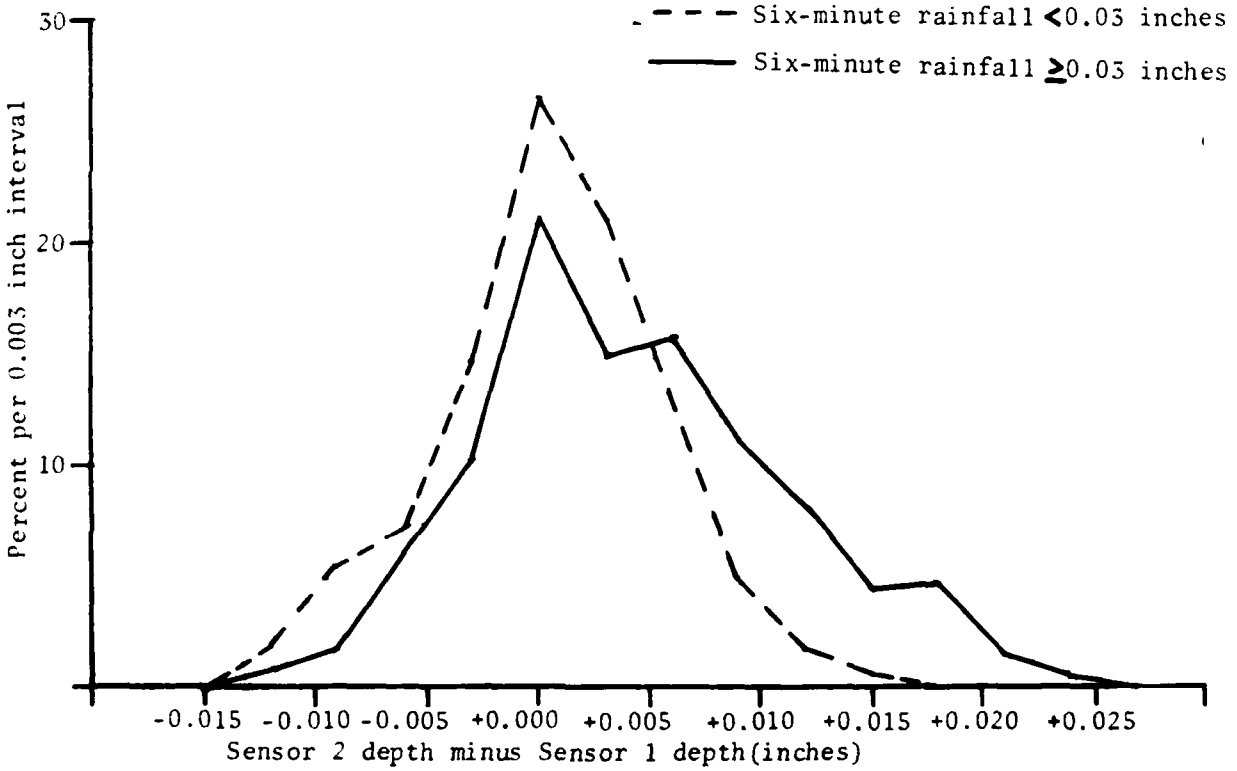

FIGURE 11 Distribution of difference between Sensor 2 water depth and Sensor 1 water depth (Spring 1985) stratified by a six-minute rainfall rate threshold of 0.03 inches.

The dividing value for S2 was chosen as 0.0325 inches and was based on examining the data set for a characteristic threshold value of S2 associated with the rise of runway water depth to moderate and large values. The two resulting distributions are shown in Figure 12. The separation into two data sets, one which is Gaussian about the zero value of S2-S1 and one which is less Gaussian, but nonetheless shows a peak in the 0.009 to 0.015 in. range, is obvious. The lack of Gaussian distribution for the >0.0325 in. distribution may be due to its smaller sample size, 80, versus 503 for the $\leq$0.0325 in. data set. The data in Figure 12 clearly show that the large differences in S2-S1 occur predominantly at the large runway water depths, and probably at the higher rainfall rates.

To further refine this descrimination by S2 water depth, we stratified the data set defined by six-minute rainfall rates $\geq$0.05 in. by the same S2 threshold, 0.0325 in. The idea was that in this shower type rainfall, the heavier the rainfall the more likely the rainfall rate at the sensor would be equal to the rate at the raingauge. As shown in Figure 13, the resulting two distributions again distinctly separate. The existence of a distribution centered around zero difference shows that even for these heavier showers, the sensor site was probably located on the shower's edge with a rainfall rate that was significantly less than that measured at the rain gauge site. On the other hand, the distribution centered around 0.015 in. no doubt represents conditions during which rainfall rate at both

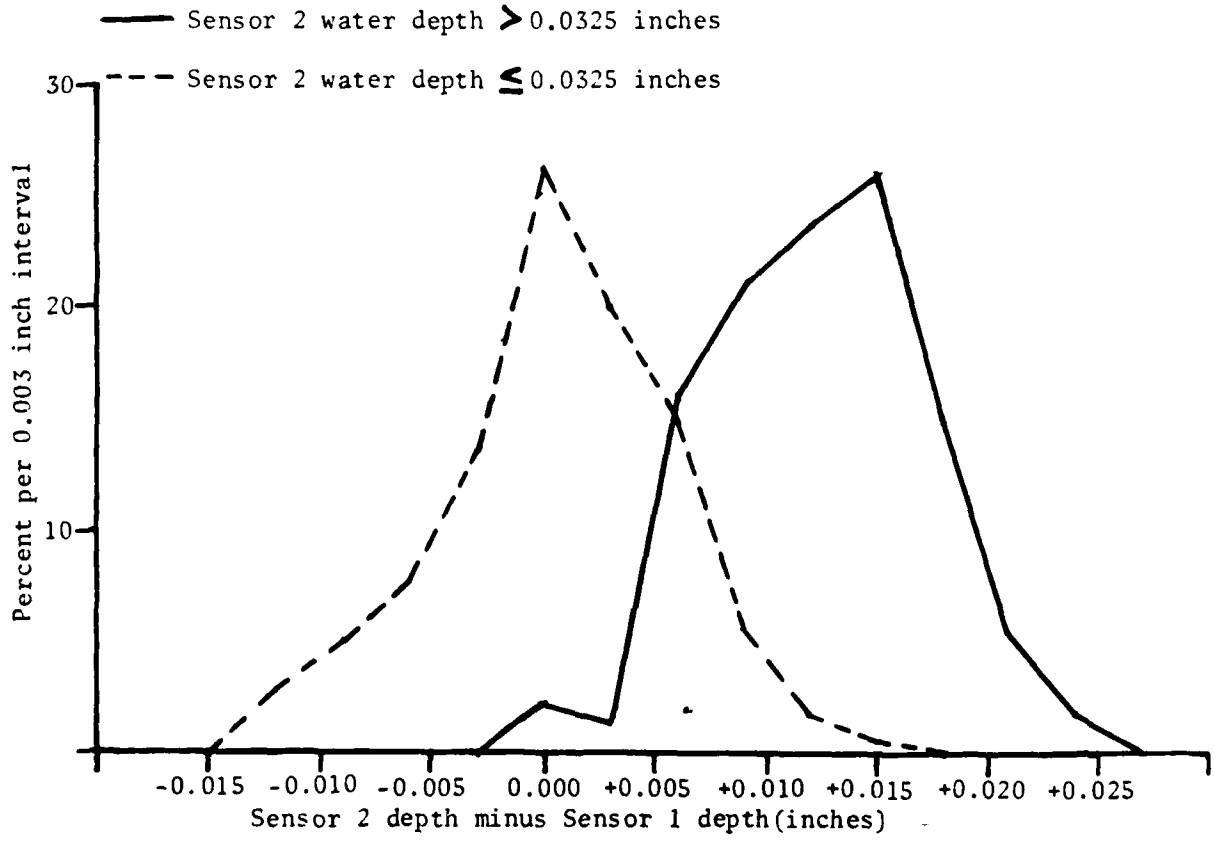

FIGURE 12 Distribution of difference between Sensor 2 water depth and Sensor 1 water depth(Spring 1985) stratified by Sensor 2 water depth threshold of 0.0325 inches.

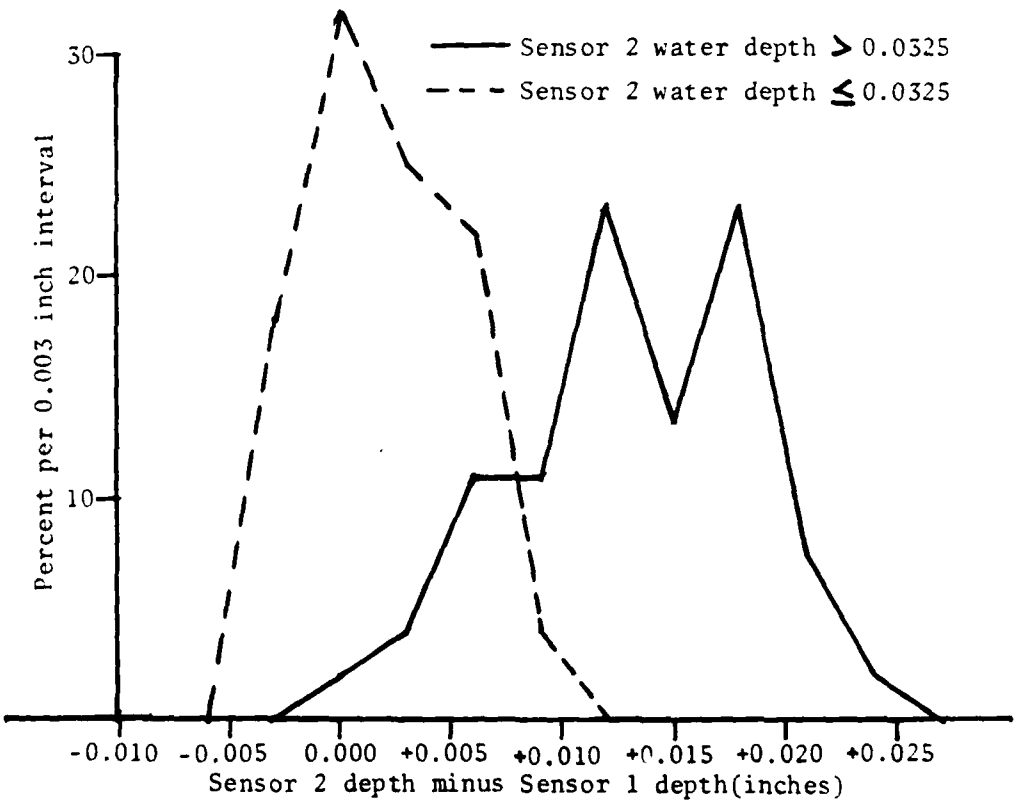

FIGURE 13 Distribution of difference between Sensor 2 water depth and Sensor 1 water depth(Spring 1985) for six-minute rainfall ≥ 0.05 inches, stratified by Sensor 2 water depth threshold of 0.0325 inches.

raingauge and sensor site are nearly equal at values $\geq$0.05 in/ 6 min. Except for the local minimum at 0.015 in. (probably a small sample artificiality) this distribution indicates that for large values of rainfall rate and correspondingly large values of runway water depth there is definitely a tendency for the water depth at S2 to be 0.010 to 0.020 inches deeper than at S1.

3.4 INDIVIDUAL LARGE S2-S1 EVENTS

To put this statistically determined set of values of S2-S1 into some physical perspective, we extracted the individual time periods with large S2-S1 values. All periods with maximum S2-S1 $\geq$0.010 inches were identified. The S2-S1 values observed in time, both before and after the maximum, were tabulated out to the first value which dropped below 0.005 in. These time sequences were then ranked according to the peak value of S2 depth measured during the rainfall event and are presented in Table 3. The S2-S1 values are presented in units of 10^{-3} inches for ease of display and discussion. Also included in the table are maximum six-minute rainfall observed during the time period, q as well as date and time of peak value of S2-S1.

The largest S2 value observed was 0.089 in., and only four values were greater than 0.050 in. Of the remaining 11 sequences, 10 fall between 0.040 and 0.050 in. There is a general tendency for the largest values of S2-S1 to occur with largest value of S2, with four of the five S2-S1 values $\geq$0.020 in. occurring with the four largest values of S2. Although there is a tendency for large rainfall to be associated

Date	Time of Peak (S2-S1)	S2 Peak (inches)	(S2-S1) x 10^{-3} (Inches)	Six-Minute Rainfall
5/27/85	1655	.089	1 18 1	0.18
3/29/85	0932	.070	0 12 17 24 22 20 19 9 -2	0.09
5/1/85	0031	.070	-14 9 16 20 17 17 11 7 5 1	0.26
5/13/85	0731	.062	-3 6 19 18 6 4	0.16
3/29/85	1354	.048	3 5 9 15 13 15 7 4	0.07
3/30/85	1858	.047	2 10 20 15 19 10 0	0.04
3/29/85	1412	.046	5 15 18 13 12 6 4	0.06
5/13/85	0843	.046	0 5 8 16 17 13 9 10 10 8 5 2	0.22
3/29/85	1450	.046	2 8 11 17 14 11 8 8 1	0.04
3/29/85	1504	.045	1 8 15 7 12 10 5 1	0.05
4/05/85	0328	.043	-4 19 3	0.05
5/13/85	1003	.042	-1 8 15 16 15 13 11 10 3	0.04
3/29/85	1600	.042	1 5 12 15 12 12 8 3	0.05
4/05/85	0658	.040	3 11 12 12 11 5 -1	0.10
4/22/85	2254	.034	4 6 10 9 12 4	0.03

Table 3 Time Sequences of (S2-S1) water depth in which (S2-S1) was greater than or equal to 0.010 inches. Sequences are ranked according to peak value of S2. Each (S2-S1) value in a sequence represents an average over the SCAN two-minute sampling period.

with large S2-S1 (four of the top eight events have rainfall values above 1.5 in/hr) the remaining 11 occur with rates $\leq$1.00 in/hr, again illustrating the problem of separation of sensor site from raingauge site.

An interesting aspect of the S2-S1 values in this table is shown in Table 4, in which the number of observations of S2-S1 above 0.007 in. from Table 3 is compared to those in the total sample (Figure 10). Notice that above 0.016 in. all values in the total sample are contained in the sequences listed in Table 3, and above 0.010 in. the sequence values are at least 50% of total sample values.

In conclusion, Tables 3 and 4 show that the large differences in S2-S1 isolated by the statistical analyses are not random, but are associated with large runway water depths, and concurrently with large rainfall rates. Threfore, this difference appears to be related to some physical property or condition which differs between the two sensors. The next section presents a possible explanation for this difference: namely, enhanced drainage around S1 resulting from the amount and distribution of epoxy which replaced the original runway material in the installation of S1.

3.5 SITING DIFFERENCES BETWEEN SENSOR 1 AND SENSOR 2

One of the basic questions about the SCAN sensors has been: Is there any significant difference between the water depth measured by a sensor installed flush with a sloping runway and

(S2-S1) (inches)	Number of Occurrences from Total Sample	Number of Occurrences from List in Table 3	Percentage Column 2/Column 1
.024	1	1	100
.023	0	0	-
.022	1	1	100
.021	0	0	-
.020	3	3	100
.019	4	4	100
.018	3	3	100
.017	5	5	100
.016	4	3	75
.015	7	7	100
.014	2	1	50
.013	6	5	83
.012	9	9	100
.011	12	6	50
.010	15	7	47
.009	13	5	38
.008	17	8	47

Table 4 Comparison of Number of Occurrences of Large (S2-S1) from Total Sample and from Sequences of (S2-S1) in which maximum value was greater than or equal to .010 inches.

that measured by a sensor installed horizontally? Sensor 1 (flush and sloping at 1° 25') and Sensor 2 (horizontal at 0° 6') were installed so that the respective water depths could be analyzed to examine this question of sensor siting.

The analysis in the previous section indicates that for light, intermittent rainfall, the water depths measured at the two sensors are equal to a value of approximately 0.030 inches. For moderate to heavy rainfall and runway water depths between 0.040 and 0.10 inches, water depth at S2 is larger than at S1 by 0.015 to 0.025 inches.

Three possibilities exist which could provide large positive values of S2-S1:

1) The S2 water depth is greater than true runway water depth.

2) The S1 water depth is less than true runway water depth.

3) The combination of 1) and 2).

Our analysis of the sensor-reported water depths in connection with the Calspan, independently measured runway water depths indicated that, on the microscale, the S2 measured water depth equaled the true runway water depth. Therefore we operate under the premise that S1 measured water depth was less than the true water depth. This situation could be due to:

1) Instrumental error or malfunction of S1.

2) Actual water depth on S1 less than actual water depth on S2.

The statistical analysis which shows Gaussian distribution of S2-S1 for S2 <0.0325 in., calibration checks (Figure 2), and the comparison of the histrograms for S1 and S2 measurements for selected values around 0.025-0.030 in. indicated that sensor S1 was working properly. (As discussed in connection with Figure 10 there was a problem with S1 at very low water depths, but this problem operates to make S1>S2). Therefore, we must conclude that the actual water depth on S1 was less than actual water depth on S2.

The three most likely possibilities which exist to produce lower water depth on S1 than on S2 are:

1) The macro runway configuration is different between the two sensors, e.g. S2 is located in a depression or S1 is located on a mound.

2) Some artificial condition exists between the two sensor installations.

3) The actual difference between flush and horizontal siting.

Possibility (1) can be ruled out as the two sensors were installed in a section of runway which was chosen for its uniform topography so that the question of flush versus horizontal could be addressed from the measuremnts. On the

other hand, some evidence exists that an artifical condition produced by the physical installation of S1 into the runway may provide for drainage so the S1 actual water depth is less than actual water depth over S2.

The photograph shown in Figure 14 shows the installation of the two sensors. The farthest sensor is S1, the flush-installed sensor and the other is S2, the horizontally installed sensor. The "X" in between the two sensors is the Point 5 used in the Calspan water depth measurements. The runway surface slopes from right to left in the picture and from bottom to top. It may be that the arm of epoxy extending away from S1 produced enhanced drainage away from S1. However, there is no way of determining if this is the case without further measurements at the site. Thus, we are left to conclude from the present set of data, that the question of whether flush versus horizontal siting produces differences in water depth measurement cannot be answered.

FIGURE 14 Photograph of SCAN Sensor Installation at Spirit of St. Louis Airport, March-May 1985. Top Sensor is Sensor 1-flush mounted; Bottom Sensor is Sensor 2-horizontally mounted.

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