TALARA AIRPORT RUNWAY REHABILITATION OPTIMIZATION BASED ON AIRCRAFT-PAVEMENT INTERACTION

By
Samuel Hautequest Cardoso, Ph.D.
Aerodromes and Ground Aids Officer
ICAO – International Civil Aviation Organization
South American Regional Office
P.O. Box 4127, Lima 100, Peru
Phones: (511) 611-8677; 9793-3706; Fax: (511) 611-8689
E-mail: shautequest@gmail.com

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ABSTRACT

Pilots' complaints about remarkable impacts of B737-400 landing gears during operations at the runway 16/34 of Talara Airport, Peru, motivated this investigation. Aircraft-pavement interaction studies were carried out and they allowed the selection of an optimized strategy for the rehabilitation of the bad areas of the runway. As a consequence, the total costs for the recuperation of those pavement areas were reduced to 35 % of the total costs for the runway restoration by using conventional approaches. In addition, the fieldwork time was reduced to 40 %. The interaction between the B-737-400 and the runway pavement surface was investigated by analyzing three longitudinal profiles obtained with rod and level. Several criteria were used to check the profiles and all of them indicated that some areas of the runway were rough. Once the problems were well known, it was possible to prescribe a very simple and efficient approach to rehabilitate the pavement critical areas. Basically, the recommended strategy was to apply deep patches only at the 20 m (66 ft) central part of the runway, considering replacement and compaction of 40 cm (16") of granular material and application of 10 cm (4") of hot mix asphalt concrete layer in three longitudinal segments equivalent to107 m, 33 m and 52 m (558 ft, 108 ft and 171 ft). In addition, a 19 mm (¾") asphalt concrete leveling course was placed in two areas with extensions of 67 m and 58 m (220 ft and 190 ft). No more pilot´s complaints were reported since the runway restoration 6 years ago.

INTRODUCTION

A comprehensive investigation of the airfield pavement surfaces characteristics should be carried out before the development of any pavement maintenance or rehabilitation design. One of the reasons for that is the importance of understanding how good and effective the aircraft-pavement interaction is.

In a very simplistic way, the studies of the aircraft-pavement interaction encompass two basic problems: the identification of aircraft aquaplaning on wet runways, or skid resistance in general, and undesirable aircraft vibration during takeoffs and landings.

Pilots, crew and passengers can easily feel the consequences of a poor interaction between aircraft and pavement. However, the pilots are those who more sense this phenomenon because aircraft vibrations caused by a rough runway are more intensively felt in the cockpit [1, 2, 3, 4].

It is also well known that each aircraft responds differently to a same runway surface roughness pattern. The reason for that is the unfortunate relation between the aircraft velocity, the aircraft response frequency (considered as a rigid body) and the types of wavelengths present at the pavement surface [1, 2, 4, 5].

One of the most rapid and effective way to obtain runway surface longitudinal profiles is the use of profilometers like the one developed by the Federal Aviation Administration (FAA). This device was designed to measure longitudinal elevation profiles and the estimation of roughness and smoothness index values. This profilometer is part of the FAA airport pavement profiling system reported by Song and Hayhoe [6]. PROFAA, FAA computer program for Roughness Index Analysis, is part of this system and it is able to generate the following outputs: simulation of physical straightedge, rolling straightedge, Boeing bump, IRI (international roughness index), California profilograph (PI – profile index), RMS bandpass and aircraft simulations (four representative commercial models).

This paper discusses how the excess of aircraft vibration during takeoffs was investigated and solved in a rational and most economic way at the Talara Airport runway, in Peru.

BACKGROUND

During some time, pilots complained about undesirable vibration effects in the B737-400 cockpit during takeoffs at the runway 16/34 of Talara Airport, in Peru. They reported remarkable impacts of the aircraft landing gears in three areas of the runway located between 600 m and 1100 m (1968 ft and 3608 ft) from its end 16.

Because the pilots started reporting this phenomenon more frequently, CORPAC (Peruvian enterprise that administrates the main Peruvian civilian airports) requested an investigation to check the pilots' information and an accurate identification of the problems and respective recommendations for their immediate correction.

According to Greenstein [7], the Peruvian Civil Aviation Authorities implemented a pavement rehabilitation program for the Talara Airport runway, in 1985/1986, because it was seriously affected by a flood that was estimated to occur at 100 year-period for that region. Coincidently, the pavement was also overloaded.

Due to the nature of the problem, all the studies were conducted taking into consideration the aircraft-pavement interaction, as it is described in the next item.

AIRCRAFT-PAVEMENT INTERACTION STUDIES

It is important to recognize that the use of profilometers is not always possible in some regions. This was the case of Talara Airport, located in the North of Peru. Furthermore, an alternate method based on rod and level was used instead. The method, which has been applied by the author since the 70's, is able to correctly identify wavelengths and respective amplitudes present in true longitudinal profiles and it also permits an accurate application of the Boeing criteria [8, 9]. Cardoso *et al* [10] has successfully used this approach for the investigation and solution of a serious wide body aircraft-pavement interaction problem at the Rio de Janeiro International Airport pre-stressed concrete runway.

The first step for using this methodology is a careful and previous planning of the field work to be carried out considering case by case. Next topic describes how the field work investigation was developed.

Field Work Investigation

The field work consisted of obtaining three runway surface longitudinal profiles located at the runway centerline and at 3 m (10 ft) at its left and right sides. Topographic leveling was carried out at 1 m (3.3 ft) interval starting from end 16, according to the approach reported by Cardoso [12] and Cardoso *et al* [13].

After the calculation of the topographic data, the profiles were carefully drawn and analyzed by applying different methods as follows:

Methods Used for the Analysis

Three methods were used to analyze the field data: the root mean square (rms) method, the investigation of resonance problems between the aircraft and the pavement surface and the Boeing criteria.

Root Mean Square Method – rms (Cardoso [12] and Cardoso *et al* [13])

This method considers that the rms values calculated for each 120 m runway segments should be classified as follows:

- Segment with rms ≤ 8.13 mm (0.32”) ⇒ acceptable roughness;
- Segment with 8.13 mm < rms < 9.15 mm (0.36”) ⇒ marginal roughness;
- Segment with rms ≥ 9.15 mm ⇒ excessive roughness.

The analysis was carried out by using the RRE (Runway Roughness Evaluation) computer program, which demonstrated that the three runway surface longitudinal profiles presented very similar results. It should be mentioned that one of the outputs of this program is the indication of the mean values for all the acceptable, marginal and excessive roughness results, as well as the rms for the entire runway. Table 1 shows that the rms values for the entire runway were 8.69 mm (0.34”), 8.40 mm (0.33”) and 8.38 mm (0.33”) for the runway centerline and for its left and right sides, respectively. Furthermore, the roughness classification for the entire runway was found to be marginal. The mean rms values for the segments with excessive roughness were very close. The higher value was observed for the runway centerline left side followed by the centerline and its right side alignment.

Even if the three profiles had several rough segments, the analysis was concentrated in the problematic areas reported by the pilots. The next step was the investigation of possible resonance phenomenon between aircraft and the pavement surface.

Investigation of Resonance Problems Between the Aircraft and the Runway Surface

The analysis was carried out considering the types of wavelengths found at the runway surface, the aircraft response frequency and the aircraft velocity at the problematic areas reported by the pilots. This approach has been used by Cardoso [14] to solve similar problems in other airports.

Table 1.
Summary of the rms estimated.

Profile location	All segments	rms mean value (mm)	(inch)
3 m (10 ft) at centerline left side	Acceptable	4.60	0.18
	Marginal	8.63	0.34
	Excessive	16.3	0.64
	Entire runway	8.40	0.33
Centerline	Acceptable	4.60	0.18
	Marginal	8.64	0.34
	Excessive	15.63	0.62
	Entire runway	8.69	0.34
3 m (10 ft) at centerline right side	Acceptable	4.62	0.18
	Marginal	8.59	0.34
	Excessive	15.25	0.60
	Entire runway	8.38	0.33

The aircraft response frequency, considering the aircraft as a rigid body, was estimated according to Equation 1 developed by Lee and Scheffel [15].

$$\log m = -2\log f + 3.35 \tag{1}$$

where:
m = aircraft mass in lb.s^2.ft^{-1}
f = aircraft response frequency in c/s (Hz)

Reworking Equation 1 in SI (metric) units:

$$\log f = \frac{3.5235 - \log m}{2} \tag{2}$$

where:
f = aircraft response frequency in c/s (Hz)
m = aircraft mass in Kg.s^2.m^{-1}

The B737-400 response frequency estimated by Eq. 2 was approximately 0.7. This value was used in Equation 3 to calculate the critical wavelengths presented in Table 2, taking into consideration the aircraft velocities, during takeoffs, at every 2.55 m/s (5 kt), starting from end 16.

$$L_c = \frac{v}{f} \tag{3}$$

where:
L_c = critical wavelength in m
v = aircraft velocity in m/s
f = aircraft response frequency in c/s (Hz)

Table 2.
Critical wavelengths as a function of the B737-400 velocity.

Velocity		Critical wavelength	
(m/s)	(kt)	(m)	(ft)
2.55	5	4	13.12
5.10	10	7	22.96
10.20	20	15	49.20
15.30	30	22	72.16
20.40	40	29	95.12
25.51	50	37	121.36
30.61	60	44	144.32
35.71	70	51	167.28
40.81	80	59	193.52
45.91	90	66	216.48
51.01	100	73	239.44
56.11	110	81	265.68
61.21	120	88	288.64
66.32	130	95	311.60
71.42	140	103	337.84
76.52	150	110	360.80
81.62	160	117	383.76
86.72	170	125	410.00
91.82	180	132	432.96
96.92	190	139	455.92
102.02	200	147	482.16

By comparing the wavelengths found in the longitudinal profiles, as indicated in Appendix 1, with the wavelengths calculated by Equation 3, for each particular aircraft velocity, no resonance problems were found between the aircraft and the runway surface. However, the analysis of these data indicates that long wavelengths found at the runway surface could excite the aircraft at velocities as high as 61.21 m/s (120 kt).

Figures 1 and 2 show that the centerline has greater number of wavelengths than its right and left sides. However, the centerline left and right sides present longer wavelengths and amplitudes than the centerline. As indicated in Appendix 1, the wavelengths for the runway centerline and its left and right sides were found to be as high as 74 m (243 ft), 91 m (299 ft) and 76 m (249 ft), respectively. Likewise, the amplitudes were found to be as high as 105 mm (4.13”), 120 mm (4.72”) and 115 mm (4.53”), respectively.

Figures 3 to 5 indicate that 71 %, 58 % and 70 % of the wavelengths at the centerline and at its left and right sides are shorter than 40 m (131 ft), respectively.

Boeing Criteria

The Boeing criteria, reported by Gervais [8] and the Boeing Commercial Airplane Group [9], consist in combining isolated bump lengths with their respective depths and classify these combinations in three zones: acceptable, excessive and unacceptable.

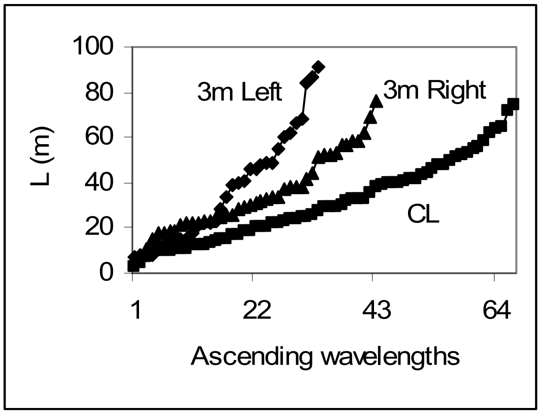

Figure 1. Wavelengths (L).

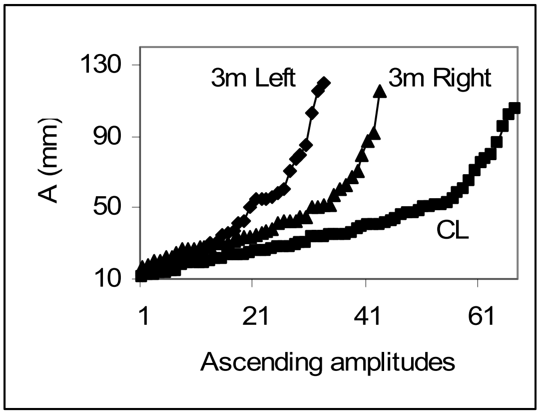

Figure 2. Amplitudes (A).

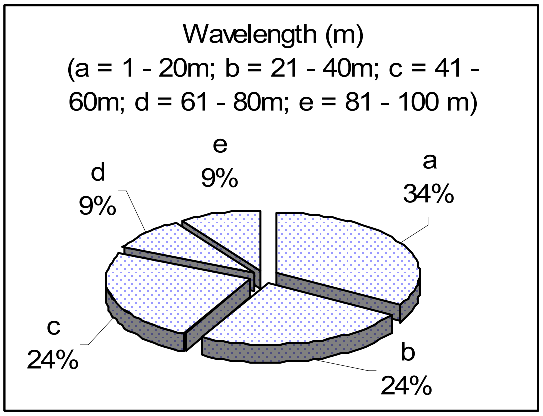

Figure 3. Wavelengths in % (CL left side).

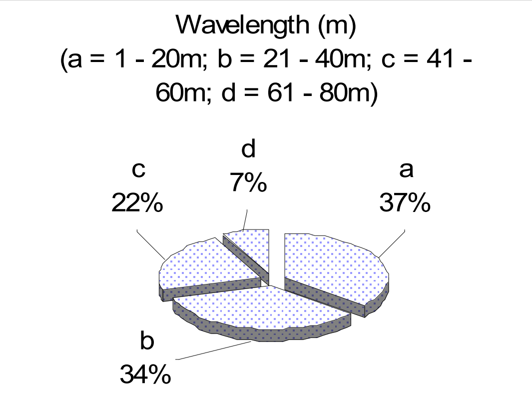

Figure 4. Wavelengths in % (centerline).

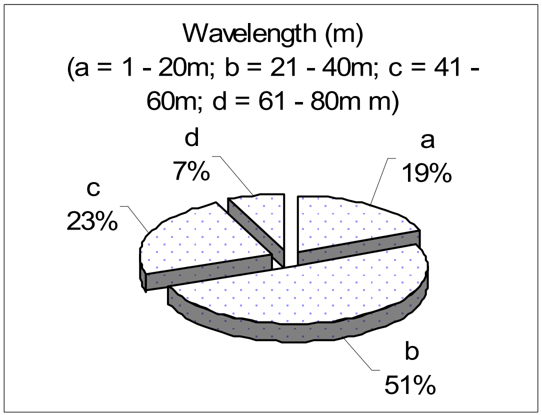

Figure 5. Wavelengths in % (CL right side).

The analysis of the profiles indicated that they had three areas with excessive bumps located between 600 m and 1100 m (1968 ft and 3608 ft) from end 16, which was in agreement with the pilot´s information. Table 03 shows a summary and a comparison between the results found by using the Boeing and the rms criteria for these areas.

Table 3.
Comparison between Boeing and rms criteria.

Location[a]		Boeing criteria				rms criteria	
Distance	Profile	L (m)	D (mm)		Diagnosis	rms (mm)	Diagnosis
			allowable	measured			
590 a 650	3m left	60	92	40	acceptable	8.28	marginal
	Cline	60	92	60	acceptable	8.50	marginal
	3m right	50	85	30	acceptable	6.32	acceptable
825 a 900	3m left	38	76	30	acceptable	6.45	acceptable
	Cline	75	100	210	**excessive**	9.60	**excessive**
	3m right	42	80	50	acceptable	7.33	acceptable
990 a 1030	3m left	10.5	46	130	**excessive**	14.78	**excessive**
	Cline	9.3	44	120	**excessive**	14.06	**excessive**
	3m right	10.0	45	90	**excessive**	12.63	**excessive**
1050 a 1110	3m left	60	92	60	acceptable	5.96	acceptable
	Cline	52	87	40	acceptable	5.01	acceptable
	3m right	23	63	50	acceptable	4.23	acceptable

[a] Distance in m from end 16; L = bump length; D = depth; rms = root mean square; 1 m = 3.28 ft; 1 mm = 0.0394”

According to the Boeing criteria, the bumps found in the segments between 825 m and 900 m (2706 ft and 2952 ft) and 990 m and 1030 m (3247 ft and 3378 ft) from end 16, indicated that the runway must be shut down immediately. Based on that, the Peruvian Civil Aviation Authority ordered the immediate runway shut down and asked for alternatives to rehabilitate the runway considering a shortage of financial resources.

STRUCTURAL ANALYSIS AND PAVEMENT DESIGN

As said before, the aircraft considered in this study was the B737-400, which main characteristics, according to Boeing Commercial Airplane Group [16], are:

Maximum takeoff weight	:	67560 Kg (148632 lb)
Main gear type	:	Dual wheels
Distance between wheels	:	77.5 cm (30.5”)
Tire pressure of the main gear wheels	:	1.275 MPa (185 psi)
Load percentage in each main gear	:	46 %

A complete structural analysis of the pavements of Talara Airport is presented by Cardoso and Nieri [11] elsewhere and its discussion is out of the scope of this paper. However, some basic information is presented in the following paragraphs.

The evaluation was based on nondestructive tests conducted with a Benkelman beam (the only available tool in the region) with the ratio of the rotating lengths equal to 1:4. The truck used to load the pavement had a single dual-wheel rear axle weighing 8200 Kg (18,000 pounds) and tire pressure of 0.55 MPa (80 psi). The methodology used was similar the one described by Cardoso *et al* [17].

Many deflection basins were obtained in order to compensate the limitations of the equipment and the variability of the results. The location, interval and number of obtained deflection basins are indicated in Table 4.

Table 4.
Location, interval and number of deflection basins.

Alignment distance from the centerline	Deflection basins	
	Interval (m)	Number
15.5 m left side	30	71
3 m left side	20	110
3 m right side	20	109
15.5 m right side	30	72
Total	---	362 deflection basins

1 m = 3.28 ft

Homogeneous segments were obtained for each alignment based on the maximum deflections by using the AASHTO Cumulative Difference Approach [18].

Representative deflection basins were obtained for each homogeneous segment, considering the 85 % percentile.

Destructive evaluation was conducted by opening cores of 40 cm x 40 cm (16" x 16") up to the subgrade in order to define the pavement structure.

Backcalculation was carried out for each representative deflection basin for obtaining the dynamic modulus of the asphalt concrete, granular and subgrade layers considering the respective pavement structures. The typical runway pavement structure had 7 cm to 10.8 cm (2.75" to 4.25") of asphalt concrete layer and 25 cm to 46 cm (10" to 18") of granular material. The pavement structure at the problematic areas had approximately 10 cm (4") of asphalt concrete and 40 cm (16") of granular material.

For this particular study, the main objective of the nondestructive evaluation was the estimation of the subgrade modulus and more specifically the subgrade CBR.

Estimate of the design subgrade CBR

The subgrade modulus values in MPa (psi) obtained with the backcalculation for the runway were: 255 (37000), 124 (18000), 276 (40000), 83 (12000), 152 (22000), 145 (21000), 207 (30000), 248 (36000), 138 (20000), 96 (13900), 114 (16500), 152 (22000), 155 (22500), 154 (22300), 248 (36000), 241 (35000), 124 (18000), 83 (12000), 138 (20000) and 103 (15000).

Equation 04, developed by Cardoso [19], was used to estimate the CBR. The development of this model was based on the analysis of 2200 deflection basins.

$$CBR_{SG} = 0.0624(MR_{SG})^{1.176} \tag{4}$$

where:

CBR_{SG} = subgrade California Bearing Ratio

MR_{SG} = subgrade resilient modulus in MPa

Table 05 presents a statistical summary of the subgrade CBR values estimated by Equation 04.

Table 5.

Statistical summary of the estimated subgrade CBR values.

Parameter	CBR_{SG}
Average	25.0 (%)
Standard deviation	11 (%)
Coefficient of variation	44.8 (%)
Sample size	20
Maximum value observed	46.0 (%)
Minimum value observed	11.0 (%)
Average – 1 Standard deviation	14 (%)

Pavement design

The pavement design for the runway segments to be recuperated was carried out according to the B737-400 design manual developed by the Boeing Commercial Airplane Group [9]. The final structure adopted was a 10 cm (4”) asphalt concrete layer and 40 cm (16”) of granular material (CBR equal or over 80 % for base course material).

POSSIBLE ALTERNATIVES FOR SOLUTION AND RESPECTIVE COSTS

All the alternatives studied considered the structural rehabilitation of the problematic areas by replacing the old pavement or by applying an asphalt concrete overlay. Three alternatives were considered:

Alternative 1: Structural rehabilitation and leveling course between 760 m and 1100 m (2493 ft and 3608 ft) from end 16

This alternative focused on the correction of the runway unevenness between 620 m and 1100 m (2034 ft and 3608 ft). The idea was to apply deep patches at some locations, only at the 20 m (66 ft) central part of the runway, considering replacement and compaction of 40 cm (16”) of granular material and application of 10 cm (4”) of new asphalt concrete layer in the following segments: 827 m to 934 m (2713 ft to 3064 ft), 992 m to 1025 m (3254 ft to 3362 ft) and 1048 m to 1100 m (3437 ft to 3608 ft) from end 16. In addition, a 19 mm (¾”) asphalt concrete leveling course would be placed in the following segments: 760 m to 827 m (2493 ft to 2713 ft) and 934 m to 992 m (3064 ft to 3254 ft). The cost estimate for this alternative was approximately US$ 96,500.00 (308,574.73 Peruvian *nuevos soles* - S/.).

Alternative 2: Overlay construction between 870 m and 1080 m (2854 ft and 3542 ft) and two chamfering

This alternative looked for the correction of the surface unevenness of the entire runway width (45 m) with the application of a 19 mm (¾”) asphalt concrete leveling course between 870 m and 1080 m (2854 ft and 3542 ft) from end 16 and application of 10 cm (4”) of asphalt concrete overlay. In addition, the runway segments between 750 m and 870 m (2460 ft and 2854 ft) and 1080 m and 1170 m (3542 ft and 3838 ft) from end 16 should be chamfered. The cost estimate for this alternative was approximately US$ 180,000.00 (576,036.59 Peruvian *nuevos soles* – S/.).

Alternative 3: Structural rehabilitation of the 20 m central part of the runway between 620 m and 1170 m (2034 ft and 3838 ft) from end 16

The objective of this alternative was to correct the runway unevenness by replacing 40 cm (16”) of granular material and application of 10 cm (4”) of asphalt concrete layer, only in the 20 m (66 ft) central part of the runway, between 620 m and 1170 m (2034 ft and 3838 ft) from end 16. The cost estimate for this alternative was approximately US$ 275,000.00 (878,622.88 Peruvian *nuevos soles* – S/.).

ALTERNATIVE ADOPTED

The first alternative was adopted and no complaints were reported by the pilots since the correction of the problem 6 years ago.

CONCLUSIONS

The aircraft-pavement interaction studies carried out in this investigation has allowed the exact identification of the areas with excessive roughness that was interfering with the B737-400 operations at Talara Airport, in Peru.

Knowing the correct location of the problematic areas, three alternatives were considered for the rehabilitation of the rough areas. The selected one consisted of the replacement of the old pavement only in the 20 m (66 ft) central part of the runway in the segments located between 827 m to 934 m (2713 ft and 3064 ft), 992 m to 1025 m (3254 ft and 3362 ft) and 1048 m to 1100 m (3437 ft and 3608 ft) from end 16. The new pavement structure was 10 cm (4”) of asphalt concrete layer and 40 cm (16”) of granular material. In addition, a 19 mm (¾”) of asphalt concrete leveling course was applied in the segments between 760 m to 827 m (2493 ft and 2713 ft) and 934 m to 992 m (3064 ft and 3254 ft) from end 16.

The selected strategy has allowed reductions of 35 % and 40 %, respectively, in the total costs and in the runway shut down time, when compared with a conventional runway pavement restoration.

The rms method has indicated that the entire runway surface was not classified as rough. However, it has shown that some segments presented excessive roughness as, for example, those located between 825 m and 900 m (2706 ft and 2952 ft) and 990 m and 1030 m (3247 ft and 3378 ft) from end 16, the same bad areas reported by the pilots. These results were confirmed by the application of the Boeing criteria.

This investigation has also allowed the conclusion that no resonance phenomena were identified between the aircraft and the runway surface. It also demonstrated that long wavelengths as long as 90 m (295 ft) were found in the profiles, which were enough to cause aircraft vibration at velocities as high as 61.21 m/s (120 kt). Another interesting finding was that 50 % to 70 % of the wavelengths of the profiles were found to be smaller than 40 m (131 ft).

DISCLAIMER

The contents of this paper correspond to the view of the author and they do not necessarily reflect the official views and policies of the International Civil Aviation Organization. Furthermore, the opinions, findings and conclusions of this paper do not constitute a standard, recommendation, specification or regulation.

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Appendix 1.
Wavelengths and respective amplitudes found at the runway surface (starting from end 16).

3m at centerline left side		Centerline		3m at centerline right side	
L (m)	A (mm)	L (m)	A (mm)	L (m)	A (mm)
8	17	11	14	8	20
8	12	12	12	6	18
8	20	7	11	25	28
12	15	19	13	22	27
15	26	19	19	34	37
13	18	10	15	34	45
13	26	4	13	11	17
18	20	3	12	30	28
7	22	17	26	15	22
66	60	15	18	26	35
49	35	12	23	52	33
21	30	11	21	32	28
34	30	12	27	58	34
91	80	11	24	33	32
28	36	20	39	19	27
41	85	15	30	69	51
39	115	13	26	38	52
55	103	40	40	44	36
46	77	30	35	28	30
49	56	74	70	18	22
48	42	52	41	19	20
40	41	33	28	29	80
46	50	39	25	51	115
22	37	50	35	37	50
23	55	33	35	18	25
22	22	53	47	23	30
12	19	72	86	21	42
15	17	27	60	38	43
87	70	24	102	25	27
84	120	46	75	53	43
68	55	29	52	42	71
62	58	22	46	62	63
60	55	23	53	22	30
Average	Std. dev.	43	47	22	41
L = 36,67	A = 46,18	26	28	23	31
S = 24,78	S = 29,51	22	19	26	38

Continue

L = wavelength (m); A = amplitude (mm); S = standard deviation; 1 m = 3.28 ft; 1 mm = 0.0394”

		Appendix 01 ⇒	continuation
L (m)	A (mm)	L (m)	A (mm)
25	19	58	50
24	21	31	60
33	26	38	45
44	58	57	92
62	48	76	57
32	38	57	87
42	51	52	67
29	50	Average	Std. dev.
38	50	L = 34,47	A = 42,54
56	55	S = 16,92	S = 21,56
29	24		
41	35		
25	19		
14	20		
35	23		
42	40		
58	36		
17	30		
40	42		
51	80		
55	34		
20	77		
65	105		
48	95		
64	65		
48	44		
40	40		
10	33		
9	34		
10	29		
20	28		
Average	Std. Dev.		
L = 30,97	A = 39,05		
S = 17,83	S = 22,11		

L = wavelength (m); A = amplitude (mm); S = standard deviation; 1 m = 3.28 ft; 1 mm = 0.0394”