NRC Publications Archive Archives des publications du CNRC

Difficulties with phase spectrum unwrapping in spectral analysis of surface waves nondestructive testing of pavements

Hunaidi, O.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

For the publisher's version, please access the DOI link below. / Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

Publisher's version / Version de l'éditeur:

<https://doi.org/10.1139/t92-055>

Canadian Geotechnical Journal, 29, 3, pp. 506-511, 1992-06

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=dc96730-6dba-49b6-9649-e4877538bab5>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=dc96730-6dba-49b6-9649-e4877538bab5>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

Difficulties with phase spectrum unwrapping in spectral analysis of surface waves nondestructive testing of pavements

Hunaidi, O.

NRCC-34150

A version of this document is published in:

Canadian Geotechnical Journal, 29, (3), pp. 506-511, June-92, DOI: [10.1139/t92-055](https://doi.org/10.1139/t92-055)

The material in this document is covered by the provisions of the Copyright Act, by Canadian laws, policies, regulations and international agreements. Such provisions serve to identify the information source and, in specific instances, to prohibit reproduction of materials without written permission. For more information visit <http://laws.justice.gc.ca/en/showtdm/cs/C-42>

Les renseignements dans ce document sont protégés par la Loi sur le droit d'auteur, par les lois, les politiques et les règlements du Canada et des accords internationaux. Ces dispositions permettent d'identifier la source de l'information et, dans certains cas, d'interdire la copie de documents sans permission écrite. Pour obtenir de plus amples renseignements : <http://lois.justice.gc.ca/fr/showtdm/cs/C-42>

DIFFICULTIES WITH PHASE SPECTRUM UNWRAPPING IN SASW NONDESTRUCTIVE TESTING OF PAVEMENTS: A CASE STUDY

M.O. AL-HUNAI

Institute for Research in Construction

National Research Council

Ottawa, Ontario K1A 0R6

ABSTRACT

Spectral Analysis of Surface Waves (SASW) is a nondestructive and in-situ method for determining the stiffness profiles of soil and pavement sites. This method involves the generation and measurement of surface Rayleigh waves. By exploiting the dispersive characteristic of these waves in layered systems, the SASW method provides information on the variation of stiffness with depth. This paper presents the results of a case study for near-surface profiling of a pavement site using the SASW method. In this study, inconsistencies were observed in the dispersion curve of the site when the usual procedure of unfolding the relative phase spectrum was followed. A correction procedure to eliminate these inconsistencies is suggested and discussed. The thickness and wave velocities of the various layers obtained with the SASW method, after applying the correction procedure, matched closely those determined from cored samples and crosshole tests.

INTRODUCTION

Nondestructive testing (NDT) methods for assessing the structural capacity of pavements are invaluable to highway agencies whose responsibility for maintenance, rehabilitation and management of highways is becoming more important due to aging highways and increasing traffic loads and volumes. The major advantage of these testing methods, as the name implies, is that they cause no physical damage to the testing medium. In addition, they are performed in-situ in a short time and require no laboratory tests. Hence, they provide efficient and economical means for assessing the stiffness profile of pavement sites, an important factor for evaluating their structural capacity. Consequently NDT methods are ideal for performing periodic condition surveys required for optimum maintenance and rehabilitation of highways.

Recent advancement and modification of the well known steady-state Rayleigh wave method (Richart et al., 1970) resulted in a promising new NDT method known as Spectral Analysis of Surface Waves (SASW) method, (Heisey et al., 1982a) and (Nazarian and Stokoe II, 1983, 1985 & 1986) among others. The SASW technique successfully reduces the field testing time and improves the accuracy of the original steady-state method. It also overcomes many of the limitations of the well known deflection-basin based methods, e.g. the Falling Weight Deflectometer or Dynaflect; however, the testing time and data analysis remain slow. The new SASW method still needs further development to attain the efficiency of other NDT methods currently in use. In addition, some difficulties and inconsistencies may arise during data reduction, as will be demonstrated in this paper.

The purpose of this paper is to present the results of a case study for the near-surface profiling of a pavement site using the SASW method. In this study, inconsistencies were observed in the dispersion curve when the usual procedure of unwrapping the phase spectrum was followed. An interpretation and a procedure to correct these inconsistencies are suggested.

SITE DESCRIPTION

The SASW method was implemented on an experimental flexible pavement section of a service road located at the campus of the National Research Council in Ottawa. Previously cored samples indicate that the asphaltic-concrete part of the road consists of two layers: a 5 cm thick layer and a newly placed overlay of about 7 cm thickness. The subbase consists of a 30 cm layer of well-compacted crushed stone. A clay layer under the subbase extends to a depth of more than 15 metres as found from soil borings. The SASW tests were performed directly on the surface of the pavement parallel to the boundaries of the road. The source-receivers array was located on the middle of the road.

SETUP, INSTRUMENTATION, AND DATA ACQUISITION

SASW Tests

The layout of the SASW testing setup is schematically shown in Figure 1. A portable dual channel FFT analyzer (ONO SOKKI Model CF-350) was utilized for recording and analyzing the data. The Common Receiver MidPoint (CRMP) array geometry was used [see Nazarian and Stokoe II (1983) for details]. The spacings between the receivers were 0.125, 0.25, 0.50, 1.0, and

2.0 metres. Two kinds of acceleration transducers were used to pick up the seismic signal, depending on the frequency range of interest. For spacings 0.125, 0.25 and 0.5 metres which are primarily used to profile shallow layers using short wavelengths, piezoelectric accelerometers sensitive in the high frequency range were employed (PCB model 308B10). On the other hand, servo-accelerometers sensitive in the low frequency range (Sunstrand model Q-flex QA700) were employed for spacings 1.0 and 2.0 metres which were used to profile deeper layers. The transducers were attached to small aluminum plates using steel studs. The plates were in turn glued to the pavement surface using 5-minute epoxy glue to ensure good coupling.

The dynamic signal is generated in the pavement using a variety of hammers depending on the frequency range of interest, which in turn influences the sampling depth. For small spacings, a lightweight small hammer was used because it tends to produce a signal with substantial high frequency content which is necessary to sample shallow layers. On the other hand, a heavy sledge hammer (5 kilograms) was employed for large spacings as it tends to induce a dynamic signal with substantial low frequency content. In order to enhance signal quality, i.e. increase signal to noise ratio, the results from five signals were averaged. An average of five signals is considered adequate (Nazarian and Stokoe II, 1985). The coherence function of the averaged data was used to judge its quality. A coherence magnitude near one corresponds to a very high signal to noise ratio. To the author's knowledge, there has been no study that has established a hard rule on what coherence magnitude should be used for SASW data. A minimum value of 0.9 was used by Nazarian and Stokoe II

(1986) as a criterion for accepting data in their evaluation of pavements. In their program for the reduction of SASW data, however, Sayyedsadr and Drnevich (1989) use a default value of 0.98 as a minimum coherence magnitude. In this study, the quality of the data was judged acceptable when the coherence function had a magnitude of at least 0.9 over the frequency range of interest. If this criterion was not satisfied, the test was repeated using different sources or impact surfaces, e.g. employing rubber pads, until satisfactory data was obtained. In most cases coherence magnitudes above 0.98 were obtained.

The hammer impact was applied at a point forming a linear array with the two receivers. The distance of this point from the near receiver was equal to the distance between the two receivers as suggested by Heisey et al. (1982a). After applying the impact on one side of the receivers' setup, the test was repeated by applying the impact on the opposite side of the receivers without moving them from their original position. In the literature, one test direction is arbitrarily termed "forward profile" and the other in the opposite direction is termed "reverse profile". Performing the SASW method with forward and reverse profiles helps to detect dipping or inhomogeneity in the site layering.

Crosshole Tests

In order to verify the results of SASW tests, crosshole tests were performed at the same location. In this section, only specific techniques of the crosshole tests performed in this study are described. Detailed treatment of this testing method can be found elsewhere (e.g. Stokoe and Hoar, 1977).

Using a drilling rig, two boreholes for motion receivers were advanced only through the pavement and the crushed stone subbase of the road. The boreholes were drilled 5 metres apart. Plastic tubes were then pushed through the clay soil to a depth of 10 metres , which was done without difficulty. A borehole for applying the impact source was located at a distance of 3 metres from the near receiver borehole. At each depth where testing was to be performed, drilling of the source borehole was stopped and drilling rods were disconnected at the surface.

Three dimensional velocity transducers packages were lowered in the two receiver boreholes to the level at which seismic testing was to be performed. The receivers were secured in place using bending-type springs. Proper orientation of the horizontal transducers was not attempted since only vertical motion is all that is needed for identifying shear wave arrival times. A hand-held hammer (4 kilograms) with an electrical trigger was used to generate an impulse by vertically impacting the top of the drilling rod in the source borehole. The receivers and the triggering transducer on the hammer were connected to a multi-channel seismograph (Geometrics/Nimbus model ES-1210F). If the signals quality was poor, gain and filter setting on the seismograph were adjusted and the impact repeated until satisfactory signals were obtained. Typical signal records are shown in Figure 2. These signal records were obtained for tests at a depth of 1.0 metre.

CONSTRUCTION OF DISPERSION CURVES

Data Reduction

The signals picked up by the receivers were recorded and Fourier transformed to the frequency domain, using the FFT analyser, in order to obtain the relative phase shift, ϕ , between the two signals as a function of frequency, f . Using in-house programs, frequency-domain data was transferred from the FFT analyser to a microcomputer for performing the dispersion curve calculations. Then the usual equations for calculating the phase velocity and wavelength were used [see Heisey et al. (1982a) or Nazarian and Stokoe (1983) for details]. The time it took each frequency component of the signal to travel between the two receivers, i.e. the time delay, is given by

$$[1] \quad t(f) = \phi(f) / 2\pi f$$

where the phase shift $\phi(f)$ is in radians and the frequency f is in cycles/second (or Hz). Knowing the distance, D , between the two receivers, the phase velocity is calculated by

$$[2] \quad V_{\phi}(f) = D / t(f)$$

and the corresponding wavelength is

$$[3] \quad \lambda_{\phi}(f) = V_{\phi}(f) / f$$

Data points that did not satisfy the following two criteria were discarded: (i) a coherence magnitude greater than 0.9 (Nazarian and Stokoe II, 1986), and (ii) a

wavelength greater than $0.5 D$ and less than $3 D$, where D is the receivers' spacing (Heisey et al., 1982a). A commercial spread sheet program (Quatro Pro) was used for performing the above calculations. The results were then plotted in the form of a dispersion curve, i.e. phase velocity versus wavelength.

It should be noted that the phase shift used in Eq. 1 is the so called "unwrapped" or "unfolded" phase. When displaying the phase spectrum, however, FFT analyzers may not use full-scale display, i.e. they may display the phase in the range ± 180 degrees and hence cause it to wrap. Phase unwrapping is performed by adding the correct number of 360 degrees cycles, as shown in Figure 3. Although some analyzers may provide a phase unwrapping option, it should not be relied upon since the phase spectrum may include some undesired parts, e.g. parts which have low coherence magnitudes.

Inconsistency of Results

The dispersion curve for the forward profile (impact point was south of the near receiver) is shown in Figure 4. From this figure, it can be seen that the parts of the dispersion curve obtained with the 0.5, 1.0 and 2.0 m spacings are inconsistent with the parts of the curve obtained with the 0.125 and 0.25 m spacings. Furthermore, the parts obtained with the 1.0 m and 0.5 m are not consistent with each other in the short wavelength range. Shown also in Figure 4 are the results of crosshole tests. The crosshole test results were adjusted to obtain the corresponding wavelength and phase velocity as explained further on. It can be seen that the part obtained with the 2.0 m spacing agrees very well with the crosshole results. On the other hand, the parts obtained with the 0.5

and 1.0 m seem to be far off the crosshole data point at the 1.0 m wavelength. The same observations were also made in the case of the dispersion curve obtained with the reverse profile, i.e. applying impacts north of the near receiver. To the author's knowledge, similar inconsistencies seem not to have been reported by other investigators.

The tests with 0.5 and 1.0 m spacings were consequently repeated, and the same results emerged. Several attempts to fit the two parts of the dispersion curve obtained with these spacings with the remainder of the dispersion curve revealed the following. For the 0.5 and 1.0 m spacing, if some cycles in the phase spectrum were included in the phase unwrapping process, they led to the observed inconsistency in the dispersion curve. This in turn led to the belief that these cycles are erroneous and should not be counted in the phase unwrapping process. When this was done, a consistent dispersion curve emerged as will be demonstrated next.

CORRECTION PROCEDURE

It seems that an erroneous cycle in the phase shift spectrum exists when a range of Rayleigh wavelengths spans two layers of substantially different properties. This observation can be demonstrated by inspecting the magnitude of transfer function between the far and near receivers shown in Figure 5a for the 1.0 metre spacing (note: transfer function is the complex ratio between the Fourier spectra of the two signals). From this figure, it can be observed that there are two segments each having an almost constant value. A transition zone exists between these two segments over which there is a gradual drop in the

magnitude of the transfer function. In order to explain this observation, consider the attenuation law of Rayleigh waves displacement amplitude in a homogeneous half-space between two points on the surface. According to this law (Richart et al., 1970), the ratio between displacement amplitudes of a given frequency at points 1 and 2, i.e. the transfer function, is given by

$$[4] \quad \frac{A_2}{A_1} = \frac{\sqrt{r_1}}{\sqrt{r_2}} \exp [- \alpha (r_2 - r_1)]$$

where A is the displacement amplitude, r is the distance from the source and α is the coefficient of attenuation due to material damping. For the receivers and source spacings ratio used in this study, the geometric attenuation factor $\frac{\sqrt{r_1}}{\sqrt{r_2}} = 0.707$, hence

$$[5] \quad \frac{A_2}{A_1} = 0.707 \exp [- \alpha (r_2 - r_1)]$$

Inspecting Eq. 5, it can be concluded that waves were propagating in two layers, each with almost a constant value of α . On the other hand, some waves were spanning the two layers to varying degrees, which explains the gradual change in the value of the transfer function over the corresponding frequency range.

Based on the above interpretation, it is concluded that wavelengths (λ) of interest, i.e. $0.5 D < \lambda < 3 D$, were propagating in the subbase of the road and/or the clay soil, for the case of the 1.0 m spacing. The segments that are

believed to correspond to waves propagating in the subbase and waves propagating mainly in the clay layer are marked on the corresponding transfer function and phase spectrum plots shown in Figures 5a and 5b, respectively. If the subbase were extending to infinity, the phase spectrum would be as indicated by the dashed line in Figure 5b. Hence unwrapping the phase for waves propagating in the subbase should follow the number of cycles traced by the dashed line in Figure 5b. For this case study, the transition zone is not included in the construction of the dispersion curve as this needs further investigation. In addition, an explanation as for the existence of the spurious cycle in the phase spectrum needs to be found. From Figure 5c, which shows the magnitude of the coherence function corresponding to data points in Figures 5a and 5b, it is obvious that poor data quality is not the reason for the existence of the spurious cycle as might be suspected. The coherence magnitude certainly exceeds 0.95 for all points, and except for very few points also exceeds the 0.98 value that might be used by other investigators. The lowest coherence value in Figure 5c is 0.95044 and the second lowest value is 0.96692. If one attempts to discard data points with coherence magnitude less than 0.98, it can be seen that the relative phase spectrum and dispersion curve would still retain the same trend. Quality of data points obtained with other receivers spacings was as high as that of data in Figure 5. The above trend of a spurious cycle was also observed in the data of the test performed with the 0.5 metre spacing.

Unwrapping the phase spectrum as explained above results in the dispersion curves shown in Figures 6 and 7 for the forward and reverse profiles,

respectively. The short wavelength portion of the dispersion curve obtained with the forward profile is expanded in Figure 6b. Contrary to the dispersion curve shown in Figure 4, the parts obtained with the 0.5 and 1.0 m spacings are now consistent with those obtained with other spacings. From these figures, it can also be seen that the dispersion curves obtained with the forward and reverse profiles are generally in good agreement, which is an indication that the layers are laterally homogeneous and the site is horizontally stratified.

In the expanded part of the dispersion curve, shown in Figure 6b, sudden fluctuations can be observed in the part obtained with the 0.25 m spacing. These are possibly caused by reflections at the lateral boundaries of the pavement layer. This effect could be reduced by proper arrangement of the source/receivers relative to the reflecting boundary (Sheu et al. 1988). Why these fluctuations are not observed in the parts obtained with other spacings, it is not known.

CONSTRUCTION OF SITE PROFILE

The shear wave velocity versus depth of a site calculated using an equivalent depth equal to $1/3$ of the Rayleigh wavelength was found to give a reasonable estimate of the actual profile of pavement sites by Szendrei and Freeme (1970) and Heisey et al. (1982b). By visually dividing the dispersion curve into several sections of constant wave velocity and using the $1/3$ wavelength criterion for calculating the equivalent sampling depth, the Rayleigh wave velocity profiles shown in Figures 6 and 7 were obtained assuming that the Rayleigh wave velocity is equal to the apparent phase velocity. Shear wave

velocity can be calculated from Rayleigh wave velocity assuming that the ratio between the latter and the former is equal to 0.92, which is considered a sufficient approximation. The results of crosshole tests at the same site are also shown in Figures 6 and 7. In these Figures, the shear wave velocities obtained with the crosshole tests were multiplied by 0.92 to obtain the corresponding Rayleigh wave or phase velocities. Earlier, in Figure 4, the depths where crosshole tests were performed were also multiplied by a factor of 3 to obtain the corresponding wavelength. It can be seen that there is excellent agreement between the results of the SASW method and the crosshole tests in spite of the fact that an approximate relationship was used for backcalculating the equivalent depth and shear wave velocity instead of formal inversion methods developed by Nazarian and Stokoe II (1986), and Hossain Drnevich (1989).

In addition, the location of layer boundaries obtained with the SASW method matched closely the actual site layering described earlier in the section on site description, except for the thickness of the old pavement layer which the SASW method overestimated by about 2 cm. The boundary marked with a question mark in Figure 6b was not expected. However, it could be an indication that the old pavement layer was constructed in two stages. In the second stage the asphalt was probably better compacted than in the first. The new pavement overlay (7 cm) is not completely detected by the SASW method. One probably has to use a receiver spacing smaller than 0.125 m and employ very high frequencies to sample this layer. Frequencies higher than 6500 Hz, which was the maximum frequency used in study, could not be used due to the frequency limitations of the available transducers. It can also be noticed that

the phase velocity of the subbase starts with a high value in the upper part and then gradually decreases toward a constant value for the lower part. This is probably caused by the compaction of the old as well as the new pavement layers which led to a higher stiffness in the upper part of the subbase.

It should finally be mentioned that for this particular site, visually dividing the dispersion curve into sections of constant phase velocity in order to determine layer thicknesses was straightforward. Most likely, this was possible because of the abrupt change in stiffness at the boundaries between the various layers. However, this may not be the case at other sites as a transition zone may exist between layers due to possible intrusion of materials from one layer to another. This is to be confirmed by performing additional SASW tests at other sites.

SUMMARY & CONCLUSIONS

The results of nondestructive evaluation of the near surface stiffness profile of a pavement site using the SASW method were presented. Inconsistencies were observed in the dispersion curve of the site considered in this study when the usual procedure of unfolding the relative phase spectrum was followed. An interpretation of this was given and a correction procedure introduced to eliminate these inconsistencies. The thickness and wave velocities of the various layers obtained with the SASW method matched closely those determined from cored samples and crosshole tests.

The correction procedure involves visual inspection and subjective evaluation of the dispersion curve and transfer function. This currently hinders

the automation of SASW's data reduction. If inconsistencies in the dispersion curve similar to those reported in this study are also observed at many other sites, alternative procedures for calculating the time delay between receivers should be explored and incorporated in the SASW method.

ACKNOWLEDGEMENTS

M. Hofmeister wrote the computer programs for exporting data to personal computers from the FFT analyser and helped with SASW tests. R. Glazer helped with instrumentation and SASW tests. A. Laberge and T. Hoogeveen performed crosshole tests. The assistance and cooperation of the above persons are gratefully acknowledged. This paper is a contribution of the Institute for Research in Construction, National Research Council of Canada.

REFERENCES

Heisey, S., Stokoe II, K.H., Hudson, R. and Meyer, A.H., 1982a.

Determination of in situ wave velocities from spectral analysis of surface waves. Research Report No. 256-2, Center for Transportation Research, The University of Texas at Austin.

Heisey, S., Stokoe II, K.H., and Meyer, A.H., 1982b.

Moduli of pavement systems from spectral analysis of surface waves. In Transportation Research Record 852, National Research Council, Washington, D.C., pp. 22-31.

Hossain, M.M., and Drnevich, V.P., 1989.

Numerical and optimization techniques applied to surface waves for backcalculation of layer moduli. In Nondestructive Testing of Pavements and back-calculation of Moduli, STP 1026, A.J. Bush III and G.Y. Baladi, Eds., ASTM, Philadelphia, Pa., pp. 649-669.

Nazarian, S. and Stokoe II, K.H., 1983.

Evaluation of moduli and thicknesses of pavement systems by spectral analysis of surface waves method. Research Report No. 256-4, Centre for Transportation Research, The University of Texas at Austin.

Nazarian, S. and Stokoe II, K.H., 1985.

In situ determination of elastic moduli of pavement systems by spectral analysis of surface waves method (practical aspects). Research Report No. 368-1F, Centre for Transportation Research, The University of Texas at Austin.

Nazarian, S. and Stokoe II, K.H., 1986.

Use of surface waves in pavement evaluation. In Transportation Research Record 1070, National Research Council, Washington, D.C., pp. 132-144.

Richart, F.E., Hall, J.R. and Woods, R.D., 1970.

Vibrations of Soils and Foundations. Prentice Hall, Inc., Englewood Cliffs, New Jersey, 414 p.

Sayyedsadr, m., and Drnevich, V.P., 1989.

SASWOPR: A program to operate on spectral analysis of surface wave data. In Nondestructive Testing of Pavements and back-calculation of Moduli, STP 1026, A.J. Bush III and G.Y. Baladi, Eds., ASTM, Philadelphia, Pa., pp. 670-682.

Sheu, J.C., Stokoe II, K.H. and Roesset, J.M., 1988.

Effect of reflected waves in SASW testing of pavements. In Transportation Research Record 1196, National Research Council, Washington, D.C., pp. 51-61.

Stokoe, K.H. II, and Hoar, R.J., 1977.

Field measurement of shear wave velocity by crosshole and downhole seismic methods. Proceedings, Dynamical methods in soil and rock mechanics, Karlsruhe, vol. 3, pp.115-137.

Szendrei, M.E. and Freeme, C.R., 1970.

Road responses to vibration tests. Journal of the Soil Mechanics and Foundations Division, ASCE, vol. 86, pp. 2099-2124.

LIST OF FIGURES

- Figure 1** Layout of the testing setup of the SASW method.
- Figure 2** Typical vertical receiver record of crosshole tests at 1.0 metre depth.
- Figure 3** Folded and unfolded phase spectra.
- Figure 4** Uncorrected dispersion curve from forward profile.
- Figure 5** (a) Transfer function, (b) relative phase spectrum, and (c) coherence magnitude obtained with 1.0 metre spacing.
- Figure 6** Corrected dispersion curve and site profile from forward profile, (a) 0 to 6 m wavelength, (b) 0 to 1 m wavelength.
- Figure 7** Corrected dispersion curve and site profile from reverse profile

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6 Continued

Figure 7

Figure 6