Development of Cross Correlation for Objective Comparison of Profiles

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16. Abstract

Standard methods of comparing two profile measurements usually place tolerances on agreement between individual elevation values over a broad waveband. A weakness of this approach is the emphasis on long wavelength content. In most road profiles, the amplitude of elevation is roughly proportional to wavelength. Thus, long-wavelength features in the road dominate the elevation profile, even though short wavelength features are often just as relevant to vehicle response. This often prevents the detection of the most important measurement problems.

This report presents a procedure for rating the agreement between profile measurements using the cross correlation function. The method is capable of rating agreement between profiles after the content is isolated to a given waveband of interest, such as that of the International Roughness Index. The conventional cross correlation method is customized to assess agreement between profile shape and overall roughness level. Thus, a high rating depends on proper measurement of the overall roughness and its spatial distribution.

The method is demonstrated for the purpose of rating agreement between profile measurements and deducing their longitudinal triggering offset. This method is intended for application in profiler comparison studies as well as profiler certification testing programs. Threshold correlation values are developed for qualification as research class, project class, and network class.

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Road profile measurement, road roughness, profiler verification, longitudinal profile

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INTRODUCTION

Standard methods of comparing two profile measurements usually place tolerances on agreement between elevation values over a broad waveband. A weakness of this approach is that it fails to emphasize the aspects of profile measurement that are more relevant to the intended application of the device. The ratings furnished by these methods for agreement between profiles does not have a direct relationship to the agreement that can be expected in summary index values. The most common method of objective profile comparison, American Society for Testing and Materials (ASTM) E-950, does not motivate a situation in which two "certified" profilers are expected to measure the same value of International Roughness Index (IRI) within a well-defined, and sufficiently tight, tolerance. When ASTM E-950 is used in profiler certification programs for construction quality control, two certified profilers often go on to produce IRI values in practice for the same site that imply differing levels of smoothness incentive pay.

This report presents an objective procedure for rating the agreement between profile measurements. The procedure is based on the cross correlation function, described by Bendat and Piersol. (*1*) A method of cross correlating profile measurements is proposed which:

- rates agreement between profiles in a given waveband, including that of a roughness index of interest,
- deduces the longitudinal distance offset between two profile measurements and compensates for it,
- searches for the linear distance measurement error in a profile measurement, and
- provides a single unitless rating of agreement ranging from -1 to 1 that may be specified in a test method.

The rating of agreement provided by this procedure represents repeatability when it is applied to two measurements of the same profile by the same device. It represents reproducibility when it is applied to two measurements of the same profile by different devices, and it represents accuracy when a measurement from one of those devices is deemed to be correct.

This method is intended for application in profiler comparison studies as well as profiler certification testing programs. The method can also be used to classify profilers for individual applications when threshold correlation values are developed. Cross correlation is superior to direct comparison of index values because it compares the overall roughness and its spatial distribution. The method yields ratings of agreement under a given set of test conditions that do not reward compensating error. Further, the method may be customized to a given application, such as measurement of a specific roughness index, or measurement of profile within a given waveband. When a correlation level is assigned to the measurement of an index, such as the IRI, it suggests a reasonable expectation of the same performance on sites of similar roughness and surface texture. This report relates the level of cross correlation for IRI output to the expected tolerance in IRI measurement, and shows how this may be done for other indices.

This report describes alternative methods already used in practice and in the classical signal analysis literature, and proposes cross correlation as an alternative. The report presents the specifics of the cross correlation method and the steps used in applying it, provides an example of the application of the method in an attempt to relate correlation levels to expected profiler performance, and describes a testing program that would help finalize the method.

EXISTING METHODS

This section presents two methods that are already in use for rating the agreement between profile measurements: (1) ASTM E-950, and (2) inspection of the gain relationship. ASTM E-950 evaluates profiler accuracy and repeatability, but it is a poor choice for either purpose.

The "gain" method verifies a profiler by comparing its measurements to a reference profile that is deemed correct. This method is a good alternative for rating profile accuracy, and would require only minor adaptation for use in rating of repeatability. Expanding the technique to include the phase relationship and coherence would provide tremendous diagnostic information for all profile comparisons. The only drawback is the complexity in setting accuracy thresholds that are based on inspection of plots, rather than a few numerical values.

ASTM E-950

The ASTM Standard E-950 is currently the most widely used method for rating the repeatability and accuracy of profilers. (*2*) The Standard includes a classification system for profilers that is based on a composite level of precision among repeat elevation measurements and a composite level of bias (or the lack thereof) in elevation compared to a reference measurement. The composite values are based on a minimum of 10 profile measurements. The individual elevation measurements are compared over a distance of 321.9 meters (1056 feet) at 0.3-meter (1-foot) intervals.

The main weakness of this approach is the emphasis on long wavelength content that results from comparison of elevation values. In most road profiles, the amplitude of elevation content is roughly proportional to wavelength. Thus, short wavelength features often appear as relatively small deviations in elevation. Comparison of elevation values, and treatment of each elevation value as a distinct measurement instead of part of the overall signal, prevents the Standard from detecting short wavelength measurement problems. The emphasis on long wavelength content also places a premium on the specific characteristics of the high-pass filter used in the profile computation. This is unfortunate, because the very long wavelength content is not of interest in most applications.

Precision

The precision of elevation measurement at a given point is rated by ASTM E-950 using the standard deviation of all elevation measurements at that location. The composite precision level over the entire profile is the average of all standard deviation values. A major weakness of this approach is the placement of a tolerance on elevation that is the same over the entire wavelength range. Road profiles, when treated as random signals, are known to commonly have elevation spectral density that decreases very rapidly with wavelength. (*3*) Performing analyses on profile elevation over a broad range of wavelengths biases the results by assigning disproportionate weight to the long wavelength content. (*4*) Short wavelength content in a profile may be significant to important road qualities, even at a low amplitude. This is because the reversals between upward and downward slope occur more quickly at shorter wavelengths, so a lower amplitude is needed to cause the same level of acceleration in a vehicle. The consequence of placing precision limits on elevation values over a broad waveband, therefore, is that short wavelength content may exhibit an unacceptable level of error with little penalty to the precision level.

Consider the influence profile elevation errors may have on the IRI. The wavelength response of the IRI is often characterized by the plot in figure 1. This plot provides the gain for profile *slope*. The response of the IRI is of the same order of magnitude for wavelengths ranging from about 1.2 to 30 meters. Errors in profile with roughly equal slope amplitudes are expected to have a similar impact on the IRI in this range.

The gain for profile *elevation* is shown in figure 2. This plot demonstrates that the IRI responds most heavily to elevation for wavelengths from 1.5 to 3 meters. Precision limits under ASTM E-950 are set on elevation over a broad waveband. Therefore, accurate IRI measurement may require precision limits that are unnecessarily restrictive for wavelength content below 1.5 meters and above 3 meters to ensure the needed precision in the band from 1.5 to 3 meters. Worse yet, the threshold values may have to be insufficient in the 1.5 to 3 meter range so that equipment can pass in the long wavelength range.

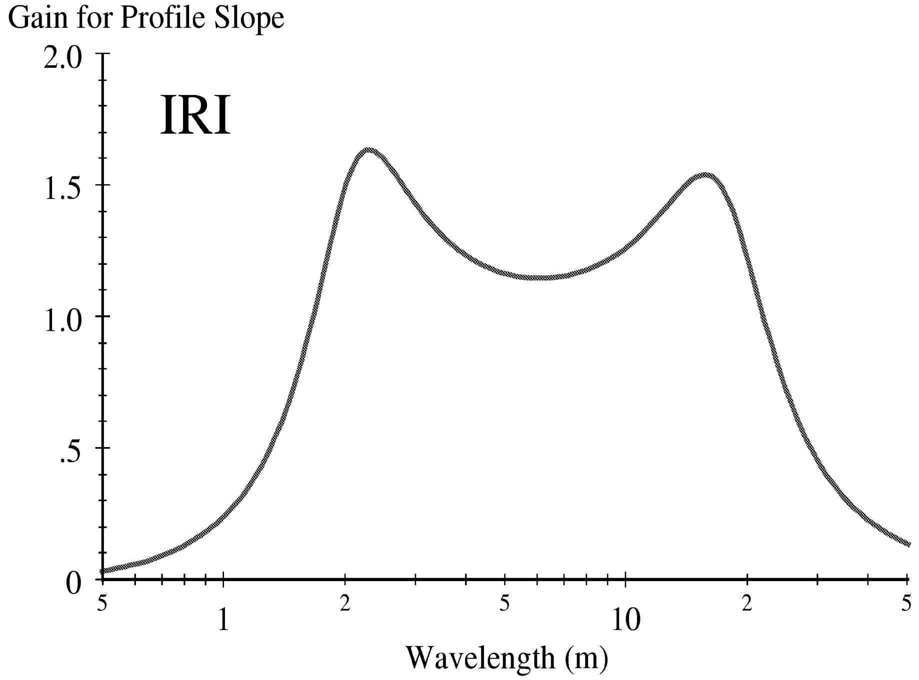

Figure 1. IRI gain for profile slope.

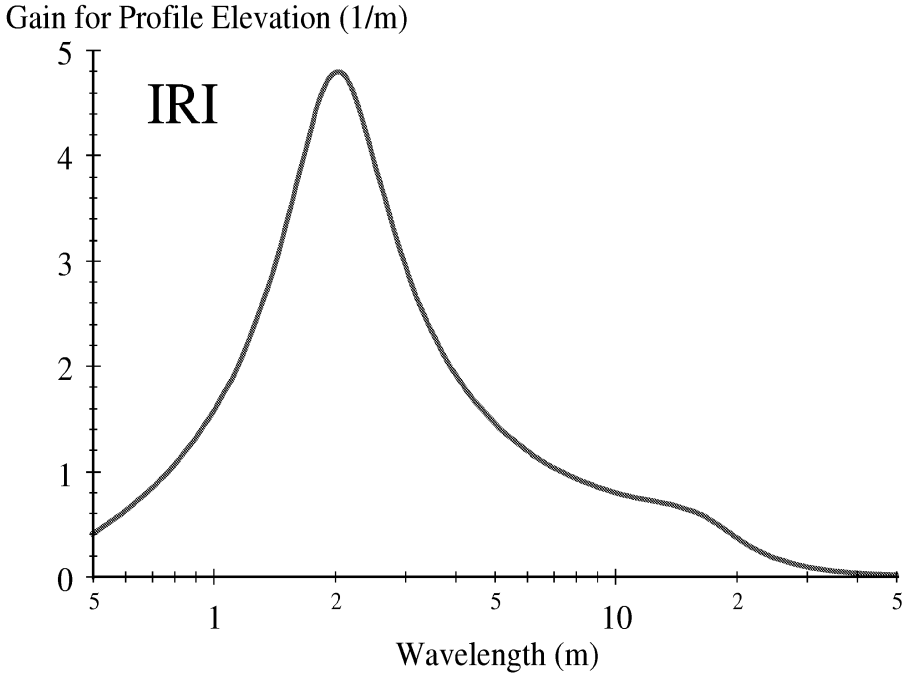

Figure 2. IRI gain for profile elevation.

This can be investigated by calculating the error level in IRI that could be imposed by sinusoidal noise without violating the precision limits specified in ASTM E-950. The Standard specifies a standard deviation limit of 0.38 millimeters for Class I equipment and 0.76 millimeters for Class II equipment. If a profile measurement of a perfectly flat road includes a sinusoidal error with a wavelength of `l`, an amplitude of A, and a phase lag of `f`, the profile P as a function of longitudinal distance x will be:

$$P(x) = A \bullet \sin\left(\frac{2\pi x}{\lambda} + \phi\right) \tag{1}$$

Over a long distance, this profile has an average rectified slope value of:

$$ARS = \frac{4A}{\lambda} \tag{2}$$

If the values of phase lag in repeat measurements are evenly distributed over the possible range, the values of amplitude (A) that correspond to the thresholds for Classes I and II are 0.54 millimeters and 1.07 millimeters, respectively, regardless of wavelength. An estimate of the error in IRI caused by the sinusoidal noise can be calculated by applying the gain at the appropriate wavelength.[1] For example, the IRI algorithm has a gain for profile slope of about 1.63 at a wavelength of 2.32 meters. Using the precision threshold for Class I, the IRI error could be 1.52 m/km:

$$\text{IRI Error} = \text{IRI Gain} \bullet \text{ARS} = 1.63 \bullet 4 \bullet (0.54\ \text{mm}) / (2.32\ \text{m}). \tag{3}$$

Figure 3 shows the theoretical error level that could exist as a function of wavelength for both precision levels. Each point in the plot is error in IRI that would be caused in the

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[1] This is only an estimate, because it does not include the influence of filter initialization.

measurement of a perfectly flat road by a sinusoidal noise that does not violate the precision limit on elevation. Some of these error levels are quite extreme. Of course, profile measurement errors rarely appear as sinusoids with random phase shift. In addition, superimposing these sinusoidal errors on a non-zero profile would lead to compensating error, because not all portions of the error component would increase roughness.

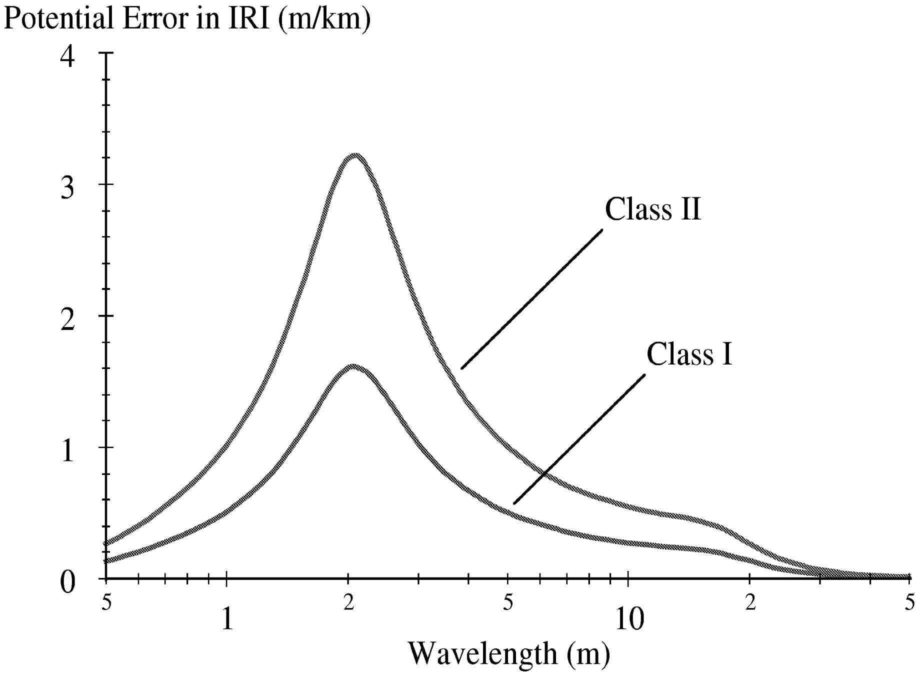

Figure 3. Theoretical error in IRI versus wavelength at Class I and II.

Profile measurement errors are much more likely to appear as random noise. This would lead to a much lower level of absolute IRI error at the same precision threshold. However, if the random noise exists over a broad range of wavelengths, figure 3 shows the relative error level that would be caused by each portion of its content. Overall, the figure demonstrates that ASTM E-950 does not protect against the effect on errors in the wavelength range from 1.5 to 3.0 meters on IRI. Profile measurement errors do occur that will appear in this range, such as incomplete correction of axle hop motion by the accelerometer, drift of a narrow laser footprint into and out of the trough of longitudinal tines, and electrical noise.

Although this example focused on measurement of IRI, the same effect will exist for other applications. This is a consequence of placing limits on the precision of elevation measurement. In any application, errors that affect the measurement of the short wavelength portion of the range of interest will always be ignored in favor of errors that affect the long wavelength portion.

Bias

In ASTM E-950, the bias in elevation measurement at a given point is rated by averaging the elevation values at that point by all repeat measurements and comparing it to the elevation value of the reference profile at that point. The difference between the two is the bias level. The composite bias level over the entire profile is the average of all bias values. The Standard specifies an average bias limit of 1.25 millimeters for Class I equipment and 2.50 millimeters for Class II equipment.

Several theoretical cases can be imagined in which limiting the bias as defined above fails to emphasize the proper aspects of agreement between profile measurements. First, ASTM E-950 does not specify a method of eliminating vertical offset between profiles, yet only rare applications of profile measurement are concerned with absolute elevation. A simple vertical offset between otherwise equivalent profiles will appear as a bias. Second, summing of individual bias values rewards compensating error when some values are high compared to the reference and some are low. Many profiles that have been low-pass filtered to exclude wavelengths over 91.4 meters, as specified in the Standard, have a average elevation value under 1.25 millimeters. It is therefore possible to qualify as a Class I instrument by reporting a profile of all zeros. A solution to this problem would be the replacement of individual bias values with their absolute values. (*5*) A thorough discussion of these and other statistical weaknesses of ASTM E-950 is provided by Li. (*6*) Third, like the precision criteria discussed above, the bias criteria places too much emphasis on long wavelength content and may ignore critical levels of error in the measurement of short wavelength features.

ASTM E-950 specifies that the amplitude and phase relationship of a profile measurement should be unaffected for wavelengths up to 60 meters. Most profilers apply a low-pass filter with a cutoff wavelength of about 90 meters that is designed to avoid modifying wavelength content below 60 meters. Not all of the this range is needed in most applications. (*4*) (Wavelengths near 60 meters affect the IRI very little.) As described above, comparison of elevation values places a premium on long wavelength content. Like the precision criteria, the bias criteria are unnecessarily sensitive to long wavelengths. The consequence of this is an undesirable sensitivity to the type of low-pass filter used in the profile computation.

In addition to placing unnecessary emphasis on long wavelength content, the bias criteria completely ignore short wavelength measurement errors. Consider the profile measurement shown in figure 4. This profile is artificially generated white noise slope, which is a rough approximation of the spectral characteristics of common profiles. The level of white noise gives this profile an IRI value of about 1.82 m/km. For this example, it will be treated as a reference measurement.

If a profiler reproduced this measurement perfectly, but applied a moving average to smooth the measurement before the bias calculation, some of the short wavelength content would be missing. (*4*) (The precise amount of content that is removed depends on the baselength of the average.) Since short wavelength features usually have low elevation amplitudes, they appear in the elevation trace as chatter but do not contribute to the larger fluctuations. Thus, applying the moving average may cause only a small absolute bias level. For example, when the profile is smoothed using a moving average with a baselength of 3 meters the trace in figure 5 is produced. The average absolute bias level of this smoothed profile, when compared to the original, is only 0.59 millimeters. This is well below the Class I limit. This implies that wavelengths under 3 meters need not even be included in the measurement to pass the bias criteria. Note that the smoothing reduced the overall IRI value to 0.71 m/km.

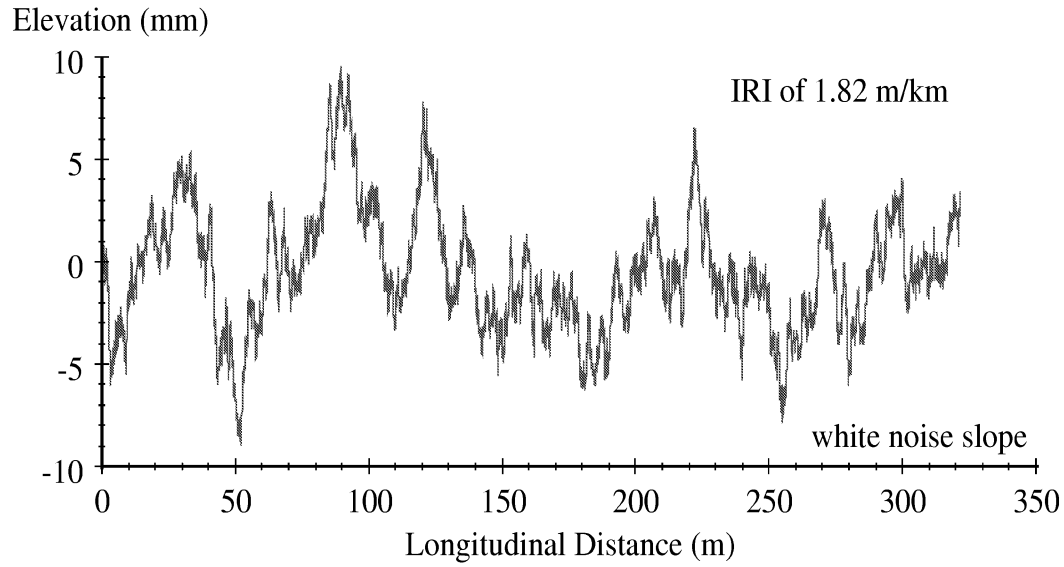

Figure 4. White noise slope profile.

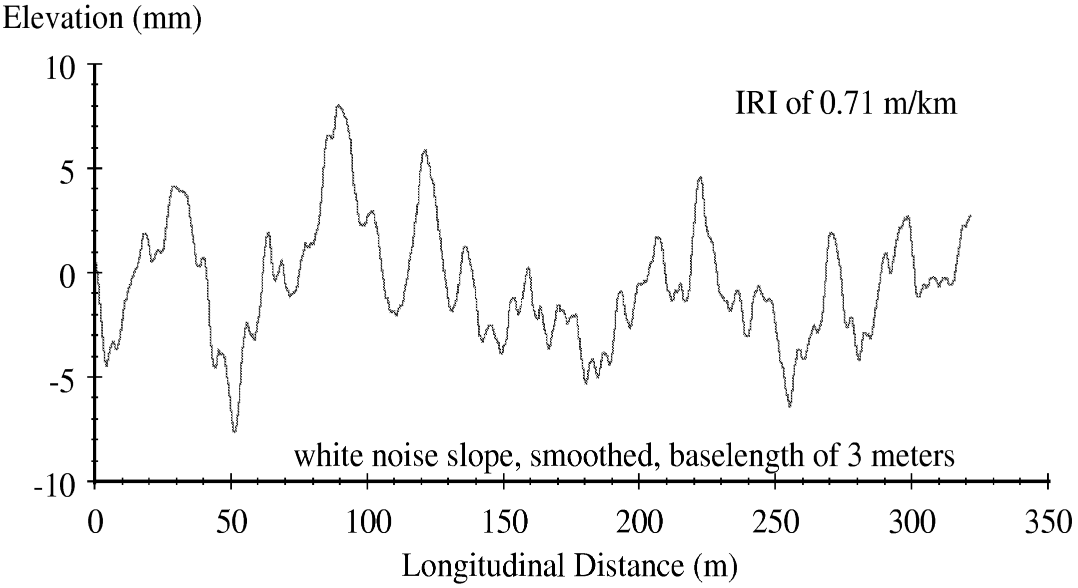

Figure 5. Profile smoothed with a 3-meter moving average.

Figures 6 and 7 show the results when this example is repeated over a range of moving average baselength values. Figure 6 shows the variation in average absolute bias that occurs as the baselength of the moving average is increased. The baselength must be increased to over 16 meters before the bias limit is violated. With a baselength of 16 meters, much of the wavelength range of interest for the IRI is removed, and most of the range of interest for the Ride Number (RN) and Michigan Ride Quality Index (RQI) is removed. This demonstrates the indifference of the ASTM E-950 bias criteria to errors or even omissions in short wavelength measurement. Figure 7 shows the variation in IRI with baselength. Note that the moving average baselength can be increased so far without violating the bias limit that a profile with an IRI of under 0.15 m/km would pass.

A significant amount of the wavelength range can also be removed before the Class I precision limit is violated. The standard deviation of "error" in elevation does not increase above 0.38 millimeters (the Class I limit) until the low-pass filter cutoff wavelength is increased to 2.75 meters. A low-pass filter with this cutoff reduces the IRI to 0.82 m/km.

Of course, the precise amount of the wavelength range ignored by the bias and precision criteria for a Class I device depends on the specific wavelength content of the reference profile and the level of genuine error that exists in the test measurements. Nevertheless, some significant portion of the short wavelength range of interest is not sufficiently captured by ASTM E-950.

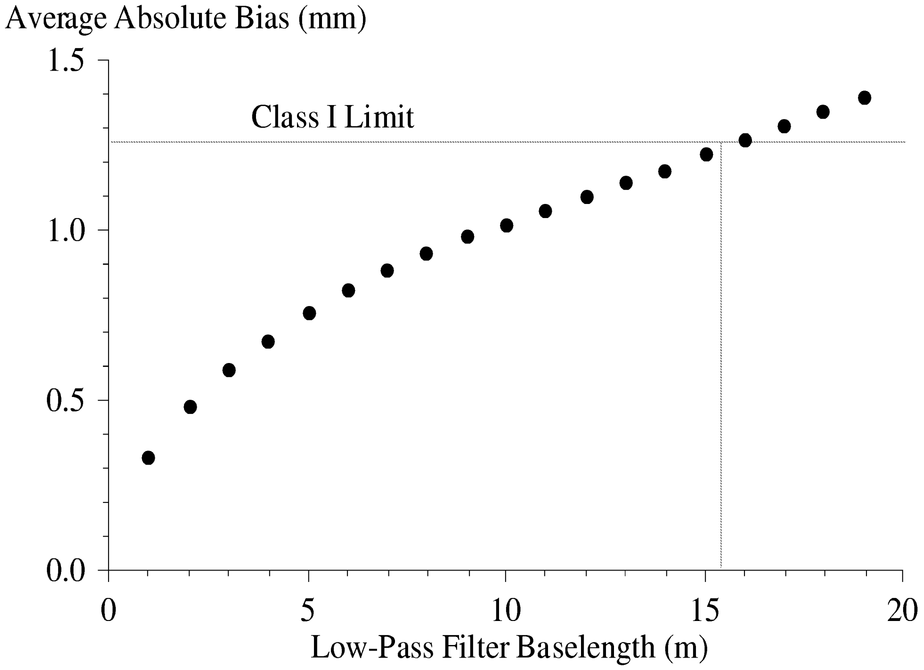

Figure 6. Absolute bias level of smoothed profiles.

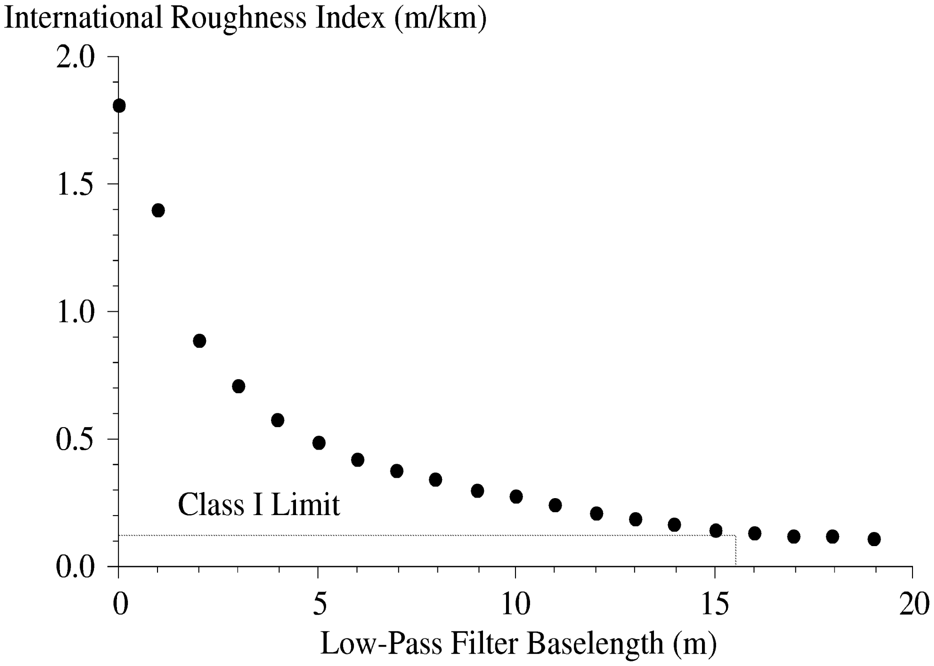

Figure 7. IRI of smoothed profiles.

Profiler Gain Limits

Hans Prem developed a method of validating pavement profile measurements using the transfer function between a reference profile and profiles collected by a (candidate) device under evaluation. (*7*) In this method, the reference profile measurement is treated as the input, and each repeat profile measurement by the candidate device is treated as output with a linear relationship to the reference profile. For each repeat measurement, a transfer function is calculated. (Strictly speaking, this is only a transfer function if the reference measurement is truly correct, and the input-output relationship is then between the actual profile of the road and the candidate profiler's output.) The transfer function gain values at each wavelength (or wave number) are then averaged across the set of repeats. Limits are placed on the composite transfer function that represent expected error limits in IRI. Figure 8 provides an example.

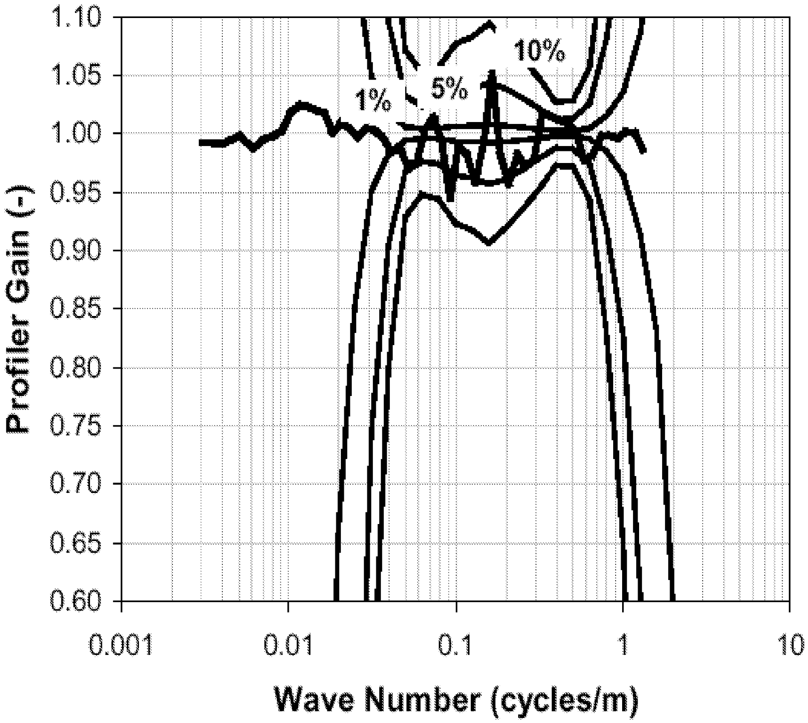

Figure 8. Profile comparison using transfer functions, after Prem. (*8*)

This approach has several advantages:

- The error limits can be customized for any index of interest, so only the relevant waveband is emphasized.
- This method may succeed with fewer measurement sites than simple comparison of summary index values. This is because profilers that may produce the same index value because of compensating error in the overall index value are not likely to produce acceptable transfer functions.
- The gain plot may provide diagnostic information about the source of error, particularly if the measurement error is confined to a narrow band or one end of the range of interest.

These advantages make the specification of profiler gain limits a useful tool for validation of profilers for pavement network evaluation, or any other application where a profiler must produce accurate index values on a lot by lot basis.

To more completely define the relationship between the reference profile and a candidate profile measurement, the phase relationship could also be examined. This would help validate the spatial distribution of roughness, which may be important if the profiler must be verified for construction quality control.

Further definition of the relationship between profiles may also be needed if the method is ever extended to examination of repeatability. This is because repeat measurements by the same profiler often consistently possess the same level and type of noise. In this case, an acceptable transfer function may be obtained despite the presence of measurement errors. With this in mind, the gain criteria should be supplemented with a specification on coherence.

The coherence function provides an assessment of the relationship between two signals at each wavelength. A high level of coherence indicates that the relationship is linear and dependent. Coherence has a maximum value of unity for a perfect relationship and degrades below unity if any noise is present. The coherence function is also penalized if any content exists in the candidate profile measurement from a source other than the actual profile. A minimum level of coherence at a given wave number between the candidate profile and the reference measurement would ensure a systematic linear relationship between them, but not a gain of one. Therefore, a rigorous specification must require a minimum level of coherence and a gain near one over the relevant waveband.

Figure 9 shows the coherence between a measurement from a lightweight profiler and a slow-speed reference measurement on a segment of moderately-rough asphalt. These measurements only appear to have a strong relationship for wavelengths over about 10 meters. (Wavelength is the inverse of wave number, so a wavelength of 10 meters corresponds to a wave number of 0.1 cycles/m.) The figure also shows the coherence between two repeat measurements by the lightweight profiler. These two measurements have a much stronger relationship for wavelengths shorter than 10 meters, but it does drop off below 1.5 meters.

Figure 10 shows the gain between the same pairs of measurements examined in figure 9. The comparison to the reference profile that produced such poor coherence also resulted in a poor comparison of spectral density, and thus, a poor gain characteristic. Through most of the wavelength range, the gain is less than one. In this analysis, the reference measurement is treated as the input and the measurement by the lightweight profiler is treated as the output. Thus, a gain of less than one indicates a lower level of roughness in the measurement by the lightweight. In fact, the IRI value produced by the lightweight was about 2.27 m/km and the value produced by the reference device was about 2.43 m/km.

The gain between the two repeat measurements by the lightweight profiler has a value near one for the entire range. As expected, the IRI values match very closely. They differ by less than 0.01 m/km. (This gain characteristic is not nearly as close to one as the example displayed in figure 8. This is partly because figure 8 shows the average of 10 individual gain characteristics.) Although the gain is very close to one for short wavelengths, the coherence function is not. This indicates that the roughness in this waveband is equal because of compensating error.

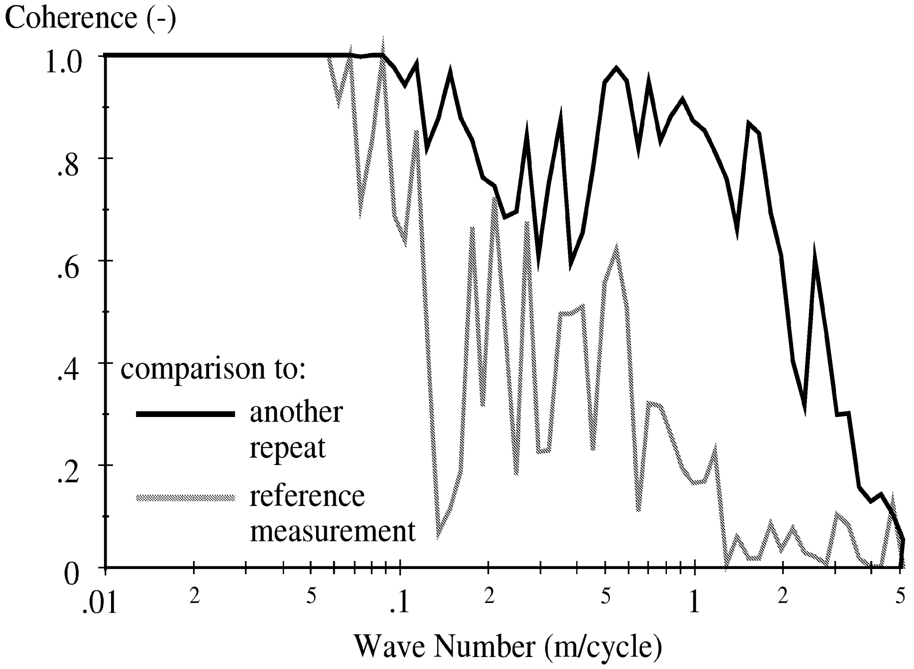

Figure 9. Coherence between road profiles.

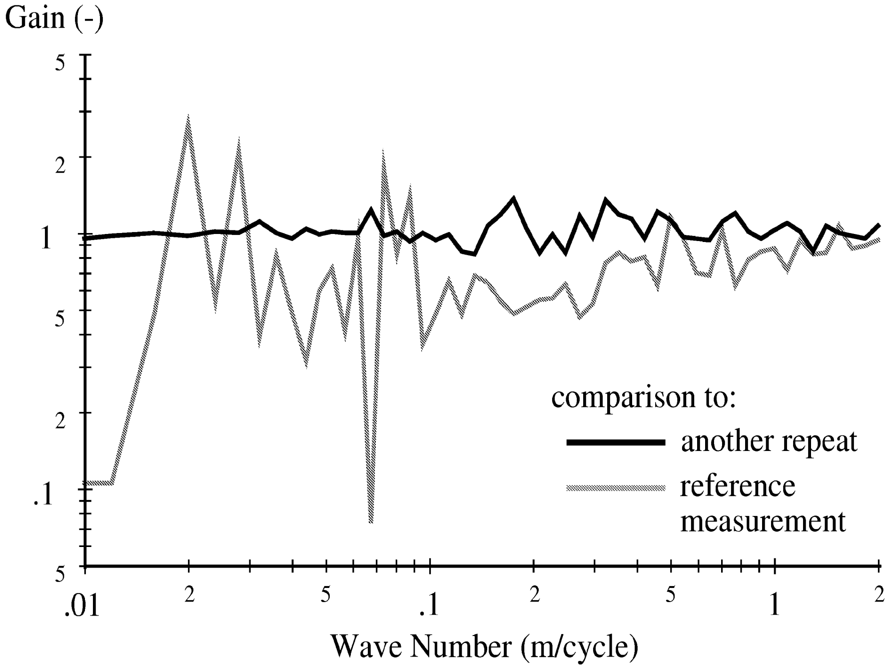

Figure 10. Gain between road profiles.

CROSS CORRELATION

This section describes the use of cross correlation for rating the agreement between profiles. Some of this material is adapted from a recent report on road profile interpretation. (*4*) This method is intended for rating of repeatability, reproducibility, or accuracy of profiles. It is based on the cross correlation function described by Bendat and Piersol for measurement of time delays between signals, rating the general dependence of one signal on another, or recovery of a given signal within noise. (*1*) In this application, it is meant to rate the relationship between two profile measurements, often when one of them is deemed to be correct. The method is adapted to detect a longitudinal distance offset between profiles and rate the agreement between them when the offset is removed. An extension to the method is also proposed for some applications when a linear distance measurement error exists.

The output of the cross correlation method yields much of the diagnostic information that is provided by the coherence and gain plots, but can be summarized in a single value for a given index of interest, or one value per waveband. When the method is customized for a given index, a high rating requires that the overall roughness level of two profiles is equivalent and that both of them distribute roughness equally within a profile. For example, when the method is applied to the IRI, a high rating requires that features which contribute to the IRI appear in the same locations with the same shape. This qualifies the method as a good candidate for certifying profilers for construction quality control, where the ability of a profiler to locate and prioritize isolated rough spots is important.

Theoretical Development

Cross correlation values are obtained by performing a convolution integral between two profiles with a given longitudinal offset. A cross correlation function is a collection of correlation values expressed versus longitudinal offset. If profiles were truly random functions, the correlation values would be zero at all values of offset except zero. Profiles are not random functions, and repeat measurements are never completely synchronized. Therefore, correlation functions between profiles of the same site fluctuate with distance, but are expected to reach a peak level at the offset needed to synchronize them.

For two measures of road profile, the cross-correlation function is defined as:

$$R_{pq}(\delta) = \lim_{L \to \infty} \frac{1}{L} \int_0^L P(x) Q(x + \delta) dx \qquad (4)$$

where P and Q are each measurements of road profile as a function of distance x. The cross correlation function, R, exists as a continuous function of the offset distance d between the profiles. Actual measures of road profile are finite in length. For a given length, L, the cross correlation function can be estimated by:

$$R_{pq}(\delta) \approx \frac{1}{L} \int_0^L P(x) Q(x + \delta) dx \qquad (5)$$

Since the profile is sampled at discrete intervals, the integral must be replaced by a summation:

$$R_{pq}(\delta) \approx \frac{1}{N}\sum_{i=1}^{N} P_i Q_{i+\delta/\Delta x} \tag{6}$$

where the subscripts indicate discrete sample numbers, collected at an interval of Dx. The number of samples, N, is the value needed to cover the overall length of interest. (The value of N will be the highest integer value that does not exceed L/Dx.) Using equation 6 requires that the offset value d is an integer multiple of the sample interval.

Equation 6 has two weaknesses when applied to road profiles. First, it yields a cross correlation function in units of elevation squared. A more desirable rating system would be normalized to produce a value of 1 for perfect correlation:

$$\rho_{pq}(\delta) = \frac{1}{\sigma_P \sigma_Q}\sum_{i=1}^{N} \hat{P}_i \hat{Q}_{i+\delta/\Delta x} \tag{7}$$

Where the hats over the letters “P” and “Q” indicate that the profiles are offset vertically to have a mean value of zero. The values s_P and s_Q represent the standard deviation of profiles P and Q, respectively. Equation 7 produces a -1 to 1 rating of the correlation, and will only produce a value of 1 when the shape of both profiles are exactly the same and they are synchronized. This is because the estimated cross correlation function is normalized by the product of the standard deviation of each profile.

A second weakness is that differences in overall roughness are not penalized by the standard cross correlation function. Two profiles that have the exact same shape but very different amplitudes would be rewarded with a perfect rating by equation 7. To compensate for this, the following factor is applied to the normalized cross correlation function:

$$f = \frac{\min(\sigma_P, \sigma_Q)}{\max(\sigma_P, \sigma_Q)} \tag{8}$$

This adjustment factor diminishes the value of correlation when the standard deviation of the profiles are not equal.

The recommended procedure for applying this method requires the profiles to be filtered, so their mean values are expected to be small. Nevertheless, the procedure also includes removal of the mean value. The computation is most efficient when each profile is shifted vertically to have a mean of zero and normalized by its standard deviation before the cross correlation function is calculated. Unfortunately, this may lead to errors when the roughness in the longer profile, “Q”, is not evenly distributed along its length. Instead, the profile must be shortened, or “cropped”, to include only the N samples needed each time the summation is performed. This is much less efficient, because the removal of the mean, calculation of the standard deviation, and filtering must be repeated for each value of offset.[2] (In equation 7, the range of profile “P” never changes so it only needs to be conditioned once, but “Q” must be conditioned every time.)

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[2] Removal of the mean and calculation of the standard deviation can be done very efficiently. Each time the offset (d) is advanced by a value of Dx (one sample), the influence of the point that is left behind is subtracted from the previous total and the influence of the new point is added.

It is essential that the same filters be applied to both profiles before using this analysis. If the profiles are not filtered similarly the results will be clouded by the differences in waveband. It is also helpful to convert the profiles from elevation to slope before computing the correlation coefficient. If elevation is used, the agreement for the longest wavelength range included in the analysis has a disproportionate influence on the results. Whatever filter is used, the best practice is to filter the profile "Q" each time the summation is performed. This is required to ensure that the effect of the filter initialization is the same in both profiles. The drawback is the filter must be applied every time a point in the cross correlation function is generated. This can be avoided if the filter initialization is not considered important by measuring a significant amount of profile ahead of the segment of interest. When that is done, both profiles may be filtered just once, as long as no part of either profile that is affected by the initialization falls within the range of samples called for by equation 7.

Synchronization

For research studies that involve several measurements of the same road section by a single device or a collection of devices, it is often desirable to "synchronize" the profiles by adjusting their longitudinal offset to make sure they all cover exactly the same stretch of road. A common way to synchronize a set of profile measurements is to simply plot them and read a distance offset from the plots. Since cross correlation provides a rating of agreement between profiles as a function of offset, it can be used to automate this process. The procedure is based on matching two measurements of a section of road and finding the offset associated with the highest level of correlation. If the profile measurements are filtered and normalized as described above, the output of the algorithm is a number between -1 and 1 that describes the agreement of the two measurements at each offset.

Figure 11 shows a *cross correlogram*, which displays the cross-correlation between a measurement by a lightweight inertial profiler and a slow-speed reference measurement as a function of offset. Both were converted to slope profile and band-pass filtered to include only content in the wavelength range from about 1.5 to 7.6 meters. Because this road profile is very similar to a random signal, the level of correlation is very poor except where the measurements are synchronized. The function has a value less than 0.2 everywhere except when the longitudinal distance offset is near 0.3 meters. The peak value of 0.898 occurs at the correct offset of 0.35 meters.

In the 1993 Road Profiler Users' Group (RPUG) calibration studies, an artificial bump was placed before and after each road section to help identify the segment of interest. (*9*) A simple bump finder was used to synchronize the sections. The profiles were then synchronized a second time using cross correlation to verify its use for this purpose. (*10*) This is described in Appendix A.

This procedure works extremely well for road profiles that are random in quality. Profiles with significant periodic content, on the other hand, may show peaks at several locations. A profile of heavily curled concrete, for example, may show a sharp increase in correlation at a regular interval equal to the slab length. Figure 12 shows and example. The figure shows a cross correlogram from two measurements of Arizona site 0213 from the Long-Tern Pavement Performance (LTPP) Study. They synchronize at an offset of 0.35

meters where the correlation level is 0.938 (which also indicates excellent agreement). On pavements with periodic content, a peak in correlation is not enough to indicate the proper offset. In most cases a peak in correlation that is much higher than the others will appear at the proper offset. When this is not true, a second cross correlogram should be calculated that includes long wavelengths only, and excludes periodic effects by ignoring the range affected by slab behavior.

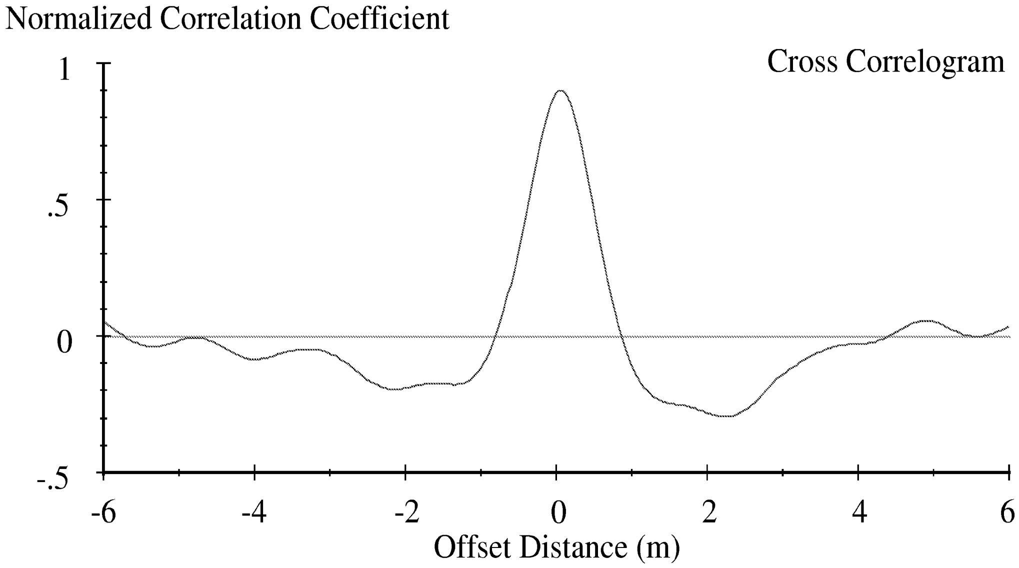

Figure 11. Cross correlogram of two profiles.

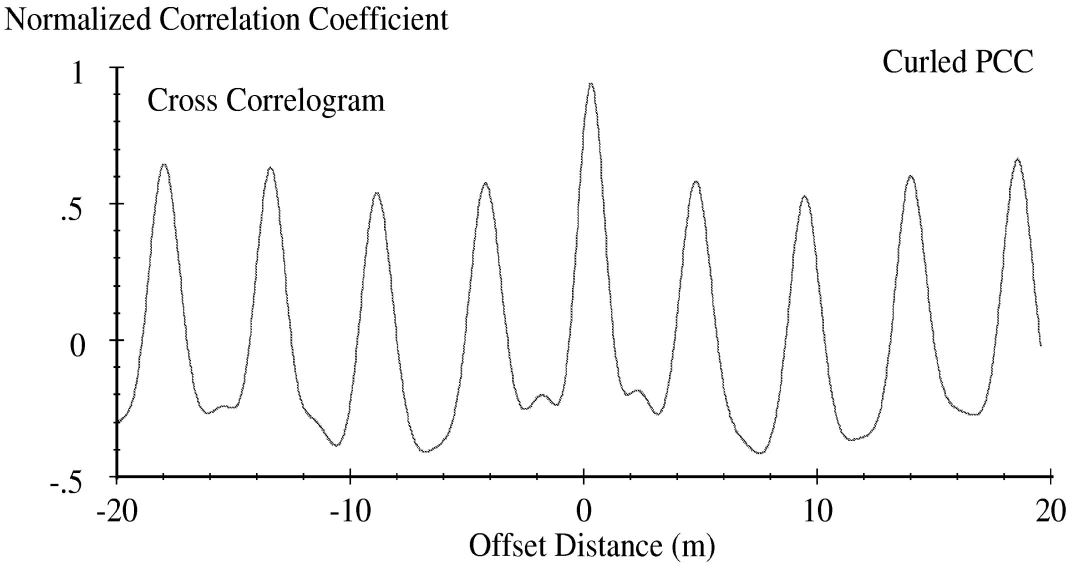

Figure 12. Cross correlogram of two profiles with periodic content.

Rating of Agreement

If the measurements compared in figure 11 agreed perfectly, the maximum correlation coefficient would be unity. However, differences between the measurements, even when they are lined up properly, still exist. This lowers the maximum correlation level. Once two measurements are synchronized, the peak correlation value used to establish their longitudinal offset provides a quantitative rating of the agreement between the them. This can be used to rate the agreement between two measurements from the same instrument (repeatability), measurements from unlike instruments (reproducibility), or agreement of a measurement to a reference profile (accuracy). Regardless of the type of comparison, cross correlation yields a rating of agreement in the waveband of interest when the profiles have been filtered identically.

Using cross correlation to evaluate agreement between profile measurements is much more rigorous than comparison of summary roughness indices. Two profilers might produce the same index value even though the profiles are not the same. In contrast, cross correlation of filtered profiles requires the same level of roughness and that rough features appear in the same location and have the same shape in each. Thus, it does not reward compensating error. This reduces the number of repeat measurements needed to reveal profile measurement problems. This method also offers the ability to diagnose measurement errors by considering a variety of wavebands. For example, bad agreement for short wavelengths but good agreement for long wavelengths suggests a problem with the height sensors and the opposite often suggests a problem with the accelerometer.

A powerful adaptation of this method is to pass two profiles through the IRI algorithm, then cross-correlate the filtered output. This has the advantage of comparing only those aspects of the profile that are important to the IRI and applying appropriate weighting to them. (Of course, if another index is of interest, filter the profile using its algorithm.) High correlation using this procedure requires not only that the overall IRI values match, but that the roughness is spatially distributed the same way in both measurements. This may be important if the profiles are intended for location of isolated rough spots, or if they are to be used in construction quality control.

Figure 13 provides an example of profiles with very high correlation. The figure shows three repeat measurements by a device after they have passed through the filters in the IRI algorithm. These signals compare to each other with an average correlation higher then 0.995. Note that the traces overlay so well that they are barely distinguishable from each other. Figure 14 provides an example of moderate correlation. It shows three repeat measurements from the same device on a different pavement section after they have passed through the filters in the IRI algorithm. These compare with an average correlation of about 0.84. The traces do not overlay nearly as well, and do not agree on the severity of roughness in locations of elevated IRI. At few locations, such as 74 and 76 meters, concentrated roughness appears in only one or two of the measurements.

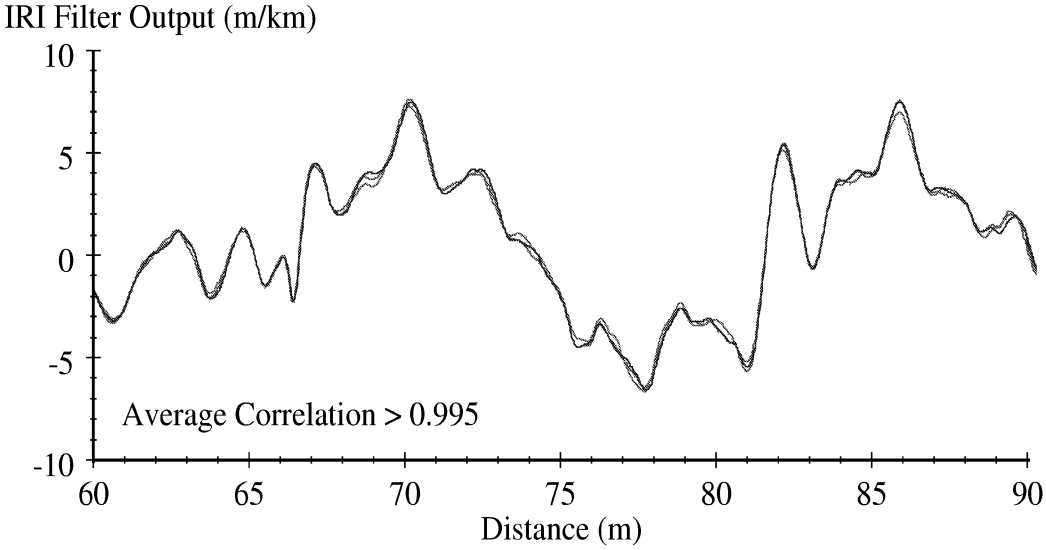

Figure 13. Three highly correlated repeat measurements.

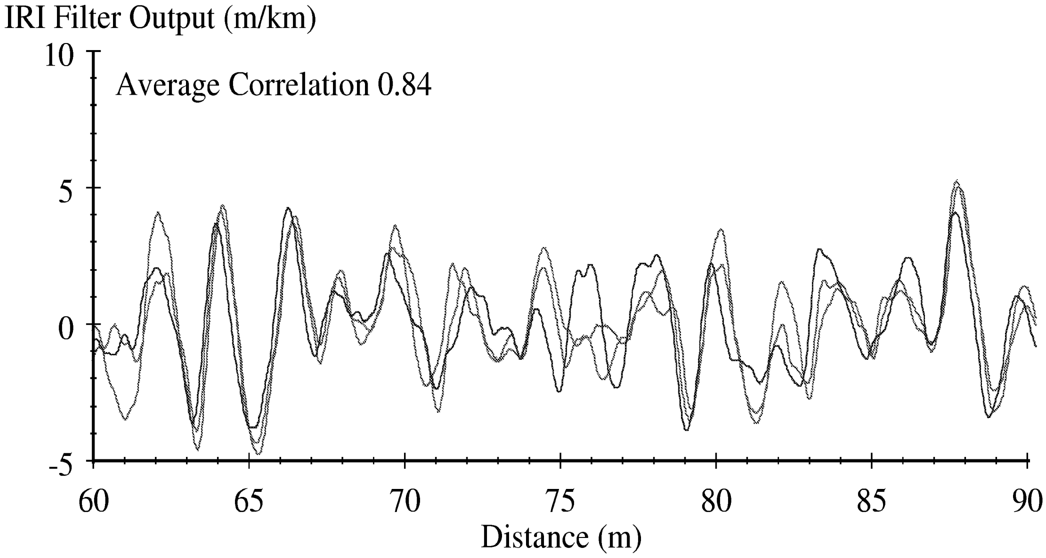

Figure 14. Three moderately correlated repeat measurements.

PROCESSING STEPS

Synchronization

Synchronization of profiles using cross correlation is performed with the following steps:

Step 1: Identify a fixed profile that is already consistent with the desired longitudinal reference. It will be considered the location reference. The profile will have a sample interval Δx, a total length L_Q, and a total number if samples N_Q ($=L_Q/\Delta x$).

Step 2: Cut a segment out of the correlated, or shifted, profile of shorter length than the reference profile, L_P. Preprocess it as follows.

Step 2a: Filter it.

Step 2b: Interpolate the filtered profile to the sample interval of the reference profile. The result is the profile q, which is a portion of the original profile P. It will have N_p samples (=L_p/Dx).

Step 2c: Offset the profile vertically so that the mean is zero.

Step 2d: Calculate the variance of the filtered, interpolated, and shifted profile $\hat{p}$. The Result is s_q.

Step 3: Apply a negative offset (d_0) to the correlated profile so that the first point in it is also the first point in the reference profile. This value of offset is equal to X_{sQ} - X_{sp}, where X_{sQ} is the longitudinal position of the start of the broader reference profile (Q), and X_{sp} is the longitudinal position of the start of the correlated profile.

Step 4: Extract the portion of the reference profile that is covered by the correlated profile. The extracted segment will cover N_p samples.

Step 4a: Filter it.

Step 4b: Offset the result vertically so that the mean is zero. The result is $\hat{q}$. Note that this signal must be conditioned *after* it has been extracted from the broader reference profile. This ensures equal application of end conditions in the two signals that will be correlated in equation 9.

Step 4c: Calculate the variance of the filtered and shifted profile over the range of interest (s_q).

Step 5: Cross-correlate the signals. In this application, the variance must be calculated over the segment of interest only to account for the common situation in which the broader profile is not stationary.

$$\rho_m = \frac{1}{\sigma_p \sigma_q} \sum_{i=1}^{N_p} \hat{p}_i \hat{q}_{i+m}$$

$$\delta_m = X_{sQ} - X_{sp} + m \bullet \Delta x \qquad (9)$$

The equation 9, the value “m” is the number of samples that are skipped at the start of profile Q. In the first application, m is zero, and the offset between profiles is X_{sQ} - X_{sp}. (The value of m is incremented from 0 to $N_Q - N_p$.)

Step 6: Shift the offset of the correlated signal by a distance equal to the sample interval of the reference profile. This amounts to shifting ahead one sample on the reference profile. (Each time this is done, increment the value of “m”.)

Step 7: If the end of the reference profile has not been reached, return to step 4.

The offset that corresponds to the highest value of r is the proper offset for synchronization. Note that the choice of a reference profile in this process does not necessarily mean that it is correct. Often, this process is simply a way to make the location referencing consistent between measurements.

Step 2a and 4a require that the profiles are filtered. It is essential that both filters are equivalent. Further, the filters must remove enough of the waveband of each profile to eliminate differences in the filtering used to produce the original measurements. In other words, when the profiles are entered into equation 9 their expected wavelength content must be equal. If the filters are chosen carefully, they will obscure differences in long and short wavelength cutoff and filter shape used by the device. For example, if the profiles are to be used strictly for the calculation of IRI, the synchronization should be done using the output of the filters from the IRI algorithm. These filters produce a slope profile that covers a wavelength range from about 1.2 to 30 meters. This is well within the intended valid waveband of most profilers. Several other filtering options are possible. The IRI filter, and five other alternatives, are listed in the following section.

The interpolation of the "correlated" profile in step 2b must be performed with care. If the sample interval of the correlated profile is similar to the sample interval of the reference profile or much larger, apply direct linear interpolation. However, if the sample interval of the reference profile is much larger than that of the correlated profile, direct interpolation is not sufficient. Conditioning must be applied to the correlated profile that is equivalent to that of the reference profile. This could include direct application of an anti-aliasing filter. It may also require modeling of the physical attributes of a low-speed reference device. For example, the application of a tire bridging or enveloping filter that reproduces the manner in which the reference device contacts the pavement.

The process outlined above provides a rating of agreement between profiles as a function of offset distance. Often, measurements differ in their distance measurement accuracy as well as their longitudinal referencing. Even small errors in measurement of longitudinal distance may compromise the correlation level. This occurs when the ratio of the smallest wavelength of interest to the overall length of the profile is on the same order of magnitude as the longitudinal distance measurement error level.

Cross correlation can also be used to quantify linear distance measurement error. This requires that correlation level is expressed as a function of both offset distance and distance measurement error level. The combination of offset distance and sample interval correction factor that produce the highest correlation to the reference are then considered "correct".

Rating of Agreement

The same process described above can be used for rating of agreement between profiles. Repeatability is rated by comparing two measurements by the same profiler on the same segment of road. When this is done, it does not matter which of the measurements is considered the "reference". This is because the sample intervals will be equal, and the process has reciprocity. (That is, the same result is obtained if the reference and correlated profiles are switched.) When profiles of unlike sample interval are compared, as will usually be the case for ratings agreement between two profilers, the choice of which measurement is considered the reference can be important. This is because the "candidate" profile measurement will be interpolated to have the same sample interval as the chosen reference. In addition, the method used to measure a road datum plane (i.e., the height sensor footprint) is deemed correct in the reference measurement.

The method of cross correlation described above for synchronization can be used directly, with the exception that the output is the correlation level (r_m). Typically, rating of agreement and synchronization are performed concurrently with this method. It is important to allow for a modest range of longitudinal offset between two profiles under comparison, even when synchronization is already done by some other method. This is because profiles may exhibit optimal synchronization at slightly different offsets when different wavebands are considered. This depends on the phase shift of the filtering done by each profiler.

When rating agreement between profiles, the output of the cross correlation method is the correlation level at the optimum longitudinal offset (and sample interval correction, if it was included). This can be calculated using equation 9, but the scale factor of equation 8 must be applied to the value of r_m:

$$\text{Agreement Level} = \rho_m \bullet f \qquad (10)$$

This penalizes the correlation level by the ratio of the variance of each signal, so two profilers must have the same level of roughness, in addition to the same shape. (It is equivalent to requiring a line of equality, instead of a best-fit line.)

Five filtering options for rating agreement are recommended :

1. The output of the IRI algorithm. This is a slope profile with frequency weighting determined by the quarter car filter using the Golden Car parameters.
2. The output of the RN algorithm. This is a slope profile with frequency weighting optimized to predict user panel ratings from experiments in Ohio and Minnesota.
3. The slope profile, passed through a four-pole Butterworth filter with cutoff wavelengths of 8 and 40 meters.
4. The slope profile, passed through a four-pole Butterworth filter with cutoff wavelengths of 1.6 and 8 meters.
5. The slope profile, passed through a four-pole Butterworth filter with cutoff wavelengths of 0.32 and 1.6 meters.

The first two options are meant to emphasize content in the profiles that is relevant to the accumulation of each index. The other three filters were included to help diagnose the source of disagreement between profiles by isolating each waveband. All of these filters are described in detail elsewhere. (*4*) Conversion to slope is a prominent feature of all five recommended filtering options. This is because most profiles exhibit much less variation in slope amplitude than elevation amplitude over the wavelength range of interest. Thus, using slope prevents the long wavelength portion of the filtered profile from dominating the results.

DEMONSTRATION USING 1993 RPUG DATA

Data from the 1993 RPUG study were used to establish a relationship between cross correlation level and expected error in overall IRI measurement. Since measurements of IRI may agree between two measurements because of compensating error, a variety of IRI error levels are possible at the same level of cross correlation between profiles. It was therefore rather difficult to establish this relationship. All profile measurements of a given wheeltrack from the 1993 RPUG experiment were compared to each other by cross correlating their filtered IRI output and by calculating the percent difference between their overall IRI values. When every possible pair of profilers were examined this way, 374,758 pairs of cross correlation and percent IRI error were generated. The 95th percentile error level in IRI at each cross correlation level was then obtained. This involved a tremendous amount of simple analysis and data assembly, and is described in detail in Appendix A, B, and C.

The results of these analyses are summarized in figure 15. The figure shows the average, RMS, and 95th percentile error in IRI observed at each cross correlation level above 0.85. A clear relationship exists between cross correlation of IRI filter output and the 95th percentile level of error in IRI that may be expected on a site of similar roughness and surface texture.

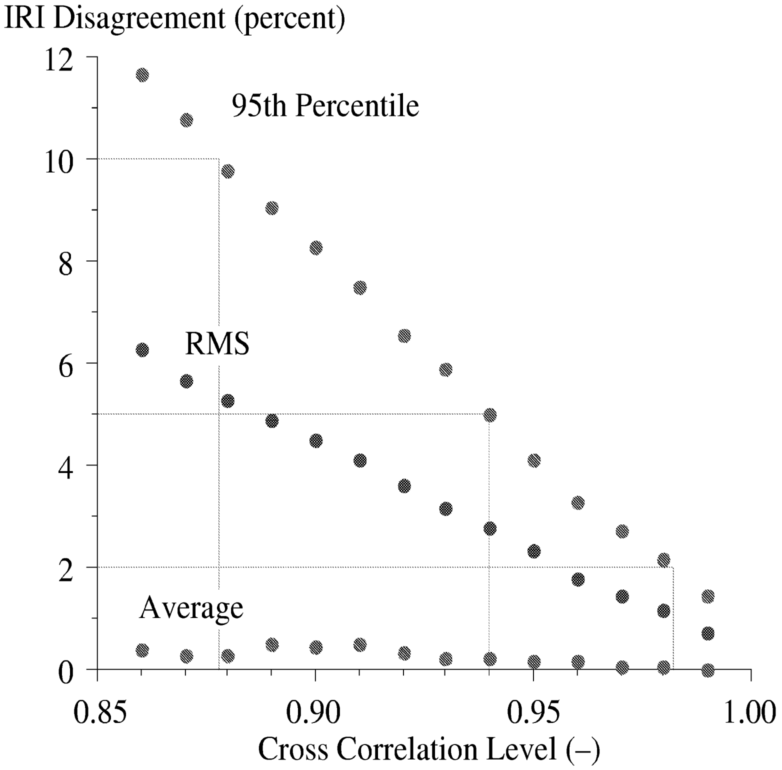

Figure 15. IRI agreement associated with cross correlation level.

RECOMMENDATIONS

It is proposed that cross correlation of filtered profile replace the precision and bias criteria of ASTM E-950 as the standard method of rating profile agreement. Cross correlation has the potential to provide a rating of agreement between profiles in a given waveband, and may be used successfully over a broader band of wavelengths if the filtering is done properly. In particular, overall profile agreement should be judged using filtered profile slope, and expected agreement in overall IRI and spatial distribution of IRI can be judged by comparing IRI filter output. Since the method is indifferent to which type of profiler makes each measurement when two profiles are compared, threshold limits on cross correlation level may be set that pertain to repeatability as well as accuracy.

Data from the 1993 RPUG were used to establish a relationship between cross correlation level of IRI filter output and agreement in overall IRI over 161 meters of road. The following thresholds are proposed for various “classes” of profiler:

- **Research Class**: At a cross correlation level of 0.98, you may expect your overall IRI measurements to agree within 2 percent of each other 95 percent of the time.
- **Project Class**: At a cross correlation level of 0.94, you may expect your overall IRI measurements to agree within 5 percent of each other 95 percent of the time.
- **Network Class**: At a cross correlation level of 0.88, you may expect your overall IRI measurements to agree within 10 percent of each other 95 percent of the time.

Further, a value of 0.94 could also be used established as a threshold for construction quality control. This must be verified by testing several profilers on new or very smooth pavement with the appropriate surface texture of each pavement type to establish that the limit is correct. In addition, the analyses must set an independent threshold that will guarantee repeatable and accurate output of the prevailing method of locating must-grinds or isolated rough spots.

Please note that the threshold correlation values were set somewhat conservatively. The data shown in figure 15 are the basis for the recommended threshold values. In figure 15, a given value of cross correlation actually represents the upper limit of a range that is 0.01 units wide. The “Project Class” threshold of 0.94, therefore, is established because values from 0.93 to 0.94 exhibited the desired performance.

The cross correlation method must be applied very carefully. Analysis of the 1993 RPUG data, and other recent studies (*11*), show that profilers will exhibit a different level of repeatability and accuracy on different types of pavement. Achieving one of the class levels listed above on a given pavement type only implies that good performance is expected on pavement of the same type and level of roughness, and of the same surface texture. Therefore, selection of test sites for profiler verification and classification is very important.

Profiling technology has improved significantly since the 1993 RPUG study. It is highly recommended that data from a more recent experiment are used to verify the threshold levels for overall performance, and develop threshold levels for verifying a profiler’s use in locating candidate hot spots for corrective action. Data are also needed to ensure that the thresholds maintain their relevance for other segment lengths. (The expected IRI error levels will change, but the trends must be verified.) In the best case, a new experiment would be designed with the help of an experienced statistician so that the threshold values above could be verified with a sufficient, but minimal experiment.

This study included theoretical derivation of the proper segment length, longitudinal distance error tolerance, phase shift limits, and sampling rules needed to apply the method. Combinations of white noise slope, elevation, and acceleration were used to generate artificial road profiles using common rules from the literature. (*12*) The cross correlation method was then applied to these profiles in an attempt to study the issues listed above. (Note that many of the results in this type of study can be derived directly in closed form, so this type of exercise is often a waste of time.) The results of these efforts are not documented here, because they were found to disagree with practical observations made in the field, and the results of a recent experiment. (*11*) The main weakness of this approach, especially in the study of sampling issues, is the lack of realistic spectral content in the short wavelength and macrotexture range. It is recommended that the artificial profiles be replaced by detailed profile measurements by a profiler with a sample interval shorter than 0.2 inches and a height sensor footprint with a radius of 0.1 inches or smaller. These measurements would replace the artificial profiles in the study.

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Appendix A: Analysis of 1993 RPUG Data

This appendix presents analyses that were performed on data from the 1993 RPUG experiment. In the 1993 RPUG experiment several profilers that normally operate in North America made multiple measurements of a small set of test sections. The experiment covered devices operated by state departments of transportation, LTPP regional contractors, profiler manufacturers, and other private operators. In each of four regions, profilers measured up to eight sections as many as ten times each. Although the state of profiling practice has improved since 1993, these data remain a rare source of measurements from multiple profilers on the same sections.

These data were used in a recent research study for the National Cooperative Highway Research Program (NCHRP) to examine the capabilities of common profilers in use in North America. (*1*) Usually, the results were used as a foundation for discussion of new experiments. The 1993 RPUG experiment served as the primary source of data in cases where a new experiment was either not warranted or not practical. The factors investigated using these measurements were (1) the accuracy of longitudinal distance measurement, (2) the repeatability of profilers from the experiment, (3) the agreement of profilers with a reference measurement, (4) the level of bias caused by coarse surface texture, and (5) the effect of operating speed on repeatability.

This appendix provides the information produced for the NCHRP study. These results serve as the basis for establishing a connection between profile cross correlation and error in IRI measurement, as described in Appendix C. A more detailed description of the 1993 RPUG experiment and the results was distributed after the 1993 RPUG meeting. (*2*)

THE RPUG EXPERIMENT

The 1993 RPUG experiment took place in four regions in the U.S. In each region, a state DOT prepared up to eight test sections 160.9 meters long. These sections, described in table A-1, were selected to cover range of surface type, roughness, and surface texture. Each profiler that participated in the experiment measured the sections in the region in which it operates. In most cases, the profilers measured each section ten times. Usually, five measurements were made at a speed near 80 kph and five were made at a speed near 64 kph. The sections were also measured using a Dipstick to provide a reference roughness value. Overall, 34 profilers took part in the study and more than 2400 measurements were made. Table A-2 lists the profilers covered in this appendix. The table provides an instrument number for each profiler that is used to identify it throughout this appendix. The table also lists the sensor type, sample interval, and manufacturer. If South Dakota is listed as the manufacturer, it means that the profiler was built in-house by a state highway using the concept documented by Dave Huft. (*3*) Many of the commercial profilers are also of South Dakota type.

Table A-1. Sections measured in the 1993 RPUG experiment.

Region	Section Number	Pavement Type	IRI Left Wheeltrack (m/km)
Mississippi	1	Asphalt Concrete	1.25
	2	Composite	0.89
	3	Composite	2.55
	4	Asphalt Concrete	3.41
	5	Portland Cement Concrete	2.94
	6	Portland Cement Concrete	1.28
	7	Portland Cement Concrete	2.72
	8	Portland Cement Concrete	1.69
Nevada	1	Asphalt Concrete	2.79
	2	Asphalt Concrete	0.80
	3	Asphalt Concrete	3.55
	4	Portland Cement Concrete	1.78
	5	Portland Cement Concrete	1.69
	6	Portland Cement Concrete	1.10
Pennsylvania	1	Asphalt Concrete	2.61
	2	Asphalt Concrete	1.06
	3	Asphalt Concrete	2.13
	4	Asphalt Concrete	2.36
	5	Portland Cement Concrete	2.78
	6	Portland Cement Concrete	3.23
	7	Portland Cement Concrete	1.89
	8	Portland Cement Concrete	1.40
South Dakota	1	Asphalt Concrete	3.89
	2	Asphalt Concrete	1.30
	3	Asphalt Concrete	1.42
	4	Asphalt Concrete	1.09
	5	Portland Cement Concrete	1.54
	6	Portland Cement Concrete	1.37
	7	Portland Cement Concrete	1.73
	8	Portland Cement Concrete	1.45

Table A-2. Devices that participated in the 1993 RPUG experiment.

Region	Inst. #	Make	Model	Sensor Type	Sample Interval (mm)	Tracks	Number of Measurements
M	MDS	Dipstick		I	305	B	8
	M01	ICC	MDR 4090	U	327	L	80
	M02	ICC	MDR 4087	U	332	B	79
	M03	ICC	MDR 4087 L	L	165	B	58
	M05	Pave Tech		U	263	B	80
	M06	K.J. Law	6900 DNC	O	152	B	100
N	N03	ICC	MDR 4090	U	326	B	59
	N04	ICC	MDR 4097	U	328	B	59
	N06	ICC		U	302	B	60
	N07	ICC	MDR 4090 L	L	160	B	61
	N08	K.J. Law	690 DNC	O	152	B	60
	N09	K.J. Law	6900 DNC	O	152	B	58
P	PDS	Dipstick		I	305	B	8
	P01	ProRut		L	50	B	80
	P02	ICC	MDR 4090	U	333	B	80
	P03	ICC		U	331	B	80
	P04	ICC	4900 LaserSDP	L	101	B	80
	P05	K.J. Law	690 DNC	O	152	B	80
	P06	ICC	MDR 4097	U	319	B	78
	P07	K.J. Law	6900 DNC	O	152	B	80
	P08	ICC	MDR 4087 L	L	165	B	74
	P73	ICC	MDR 4195	U	342	B	80
	P74	ICC	MDR 4195	U	342	B	79
	P75	ICC	MDR 4195	U	343	B	80
	P76	ICC	MDR 4195	U	340	B	80
S	SDS	Dipstick		I	305	B	8
	S01	ICC		U	323	B	65
	S02	South Dakota		U	305	L	80
	S03	Pave Tech		U	331	L	80
	S04	South Dakota		U	305	L	77
	S05	K.J. Law		O	152	B	47
	S06	South Dakota		U	305	L	79
	S08	K.J. Law	6900 DNC	O	152	B	77
	S10	ARAN	4300 LaserSDP	L	204	B	58
	S11	Pave Tech		U	335	B	40
	S12	South Dakota		U	305	L	80

M - Mississippi
N - Nevada
P - Pennsylvania
S - South Dakota
I - Inclinometer
O - Optical
U - Ultrasonic
L - Laser
L - Left
B - Both (Left and Right)

LONGITUDINAL DISTANCE MEASUREMENT

The 1993 RPUG tests were designed to eliminate errors in longitudinal positioning of the measurements. To help maintain a consistent starting position in each measurement, an artificial bump was placed on the road before and after each section. The bumps were about 6 millimeters high, 0.46 meters long, and were located 30.5 meters upstream and 15.2 meters downstream of the section of interest. The data files used in the analyses reported in this appendix were lined up using cross-correlation rather than the bumps in the profile. The cross-correlation program shifts the "zero" location of every file to match a reference measurement, usually by the Dipstick. Since the sections were all 160.9 meters long, the artificial bumps should appear 206.7 meters apart at the longitudinal locations –30.48 and 176.17 meters. This was used to check the procedure for lining up the sections.

The distance between the bumps measured by each profiler was also used to test the accuracy of their longitudinal distance measurement. Not all of the measurements included enough profile surrounding the section of interest to contain both bumps. Some other measurements were long enough, but no bump appeared in the expected location. (These cases prompted some verification to make sure the section was lined up properly.) Naturally, the measurement of longitudinal distance was only checked on measurements where both bumps appeared clearly in the profile. Table A-3 lists the results for each profiler. The table lists the number of measurements that included both bumps, the average distance between them, and the error in percent. The table also lists the average offset level in units of length. A negative offset means the profiler underestimated the distance and a positive offset means the profiler overestimated the distance. In most cases, the offset error (or bias) in longitudinal distance measured by a profiler was consistent from run to run. Thus, the average offset error represents the value expected in a single run. The offset error is listed side-by-side with the sample interval to identify cases where the error was not much larger than the sample interval.

Table A-3 demonstrates that most profilers measure longitudinal distance fairly accurately. Twenty-one of the thirty profilers measured the distance between the bumps consistently within two profile samples. Since each bump can only be detected in the profile within one sample, these twenty-one devices are considered correct. Three of the profilers exhibited an error level greater than 1 meter, or about 0.5 percent. This is more serious: A bias in longitudinal distance measurement of 0.5 percent or more should prompt recalibration of the distance measurement instrument.

The profilers that exhibited the greatest error in longitudinal distance measurement may have slowed down significantly over the bumps to avoid damage to the vehicle, or simply because the bumps were not within the section of interest in the study. If the error was caused by extremely low-speed operation, it is of lesser concern because it does not represent typical operation of the profilers.

Table A-3. Longitudinal distance measurement accuracy.

Region	Inst. Number	Number of Measurements	Average Separation (m)	Percent Error	Offset (mm)	Sample Interval (mm)
M	M01	73	206.15	-0.25	-509	327
	M02	76	208.35	0.82	1700	332
	M03	50	206.14	-0.25	-518	165
	M05	72	206.40	-0.12	-258	263
	M06	99	207.19	0.26	539	152
N	N04	59	206.51	-0.07	-149	328
	N08	60	206.74	0.04	88	152
	N09	57	207.75	0.53	1094	152
P	P01	79	206.41	-0.12	-242	50
	P02	80	206.66	0.00	8	333
	P03	80	207.34	0.33	683	331
	P04	76	206.85	0.09	193	101
	P05	70	206.79	0.07	137	152
	P06	68	206.61	-0.02	-47	319
	P07	80	206.62	-0.02	-34	152
	P08	74	206.24	-0.20	-415	165
	P73	79	206.72	0.03	62	342
	P74	79	206.59	-0.03	-62	342
	P75	80	206.53	-0.06	-128	343
	P76	80	206.69	0.02	32	340
S	S01	64	206.18	-0.23	-474	323
	S02	78	206.46	-0.09	-191	305
	S03	55	206.46	-0.09	-194	331
	S04	65	206.57	-0.04	-80	305
	S05	47	206.51	-0.07	-139	152
	S06	70	205.87	-0.38	-786	305
	S08	77	206.48	-0.09	-176	152
	S10	53	203.21	-1.67	-3444	204
	S11	40	206.40	-0.12	-256	335
	S12	70	206.63	-0.01	-22	305

M - Mississippi N - Nevada P - Pennsylvania S - South Dakota

REPEATABILITY

The repeatability of a profiling device is its ability to produce the same result in multiple runs with minimal random error. It is very important that a profiler measure roughness with reasonable repeatability, since a device that is not repeatable has no hope of being accurate. A lack of repeatability also suggests that a random error source is present in the measurement. Some aspects of the pavement surface shape affect repeatability through no fault of a profiler. Transverse, longitudinal, and temporal variations in pavement roughness may introduce scatter into a set of measurements, even if a perfectly repeatable profiler was used.

The goal of this section is to present statistics that summarize the level of repeatability of each profiler for measurement of an overall roughness index value. The 1993 RPUG data are a good source for judging repeatability without the confounding influence of variations in pavement roughness with time and position. Each profiler visited each section once and made all of the measurements of a section in a short time span, so variations in roughness with time should not affect the results. The measurements are also lined up longitudinally. Although the lateral position of the profilers was not strictly controlled, paint marks were placed every 7.6 meters along the left wheeltrack of each section to help guide the drivers along a consistent path. At the very least, these paint marks reminded the drivers of the importance of consistent lateral positioning in the experiment.

International Roughness Index

Most of the profilers listed in table A-2 measured all of the sections in their region ten times. To quantify the scatter exhibited by a profiler, each IRI value was normalized by the average of the ten measurements on a given wheeltrack of a given section. For example, the ProRut measured eight sections ten times each. The IRI was computed for the left and right wheeltrack in each measurement, for a total of 160 roughness values. Each set of ten measurements from one side of a section was normalized by its average, and the values on all sixteen wheeltracks were compiled into a histogram, shown in figure A-1. Of course, the average of the 160 values in the figure is 1. The scatter is an indication of the level of repeatability. The standard deviation of the values in the figure is 0.027. This means that about 68 percent of the measurements by the ProRut were within 2.7 percent of the prevailing average for a given wheeltrack. A more relevant way to summarize the performance than the standard deviation is to set a limit for the scatter and see how many measurements fall within the limit. For example, the histogram shows that most of the roughness values (150 out of 160) measured by the ProRut are within 5 percent of the section average. If the limit is set at 2 percent, only 101 of measurements “pass.”

IRI values from all of the profilers were compiled in this fashion as a means of characterizing each profiler’s repeatability. The results should not be interpreted too precisely, since not every profiler made the same set of measurements. Not all of the profilers within a region measured all of the sections exactly ten times. Some profilers, usually the South Dakota type, measured only the left wheeltrack. Each region had a unique set of sections, so only comparisons of major trends should be made across all of the regions. Nevertheless, some of the trends are so strong that they are meaningful.

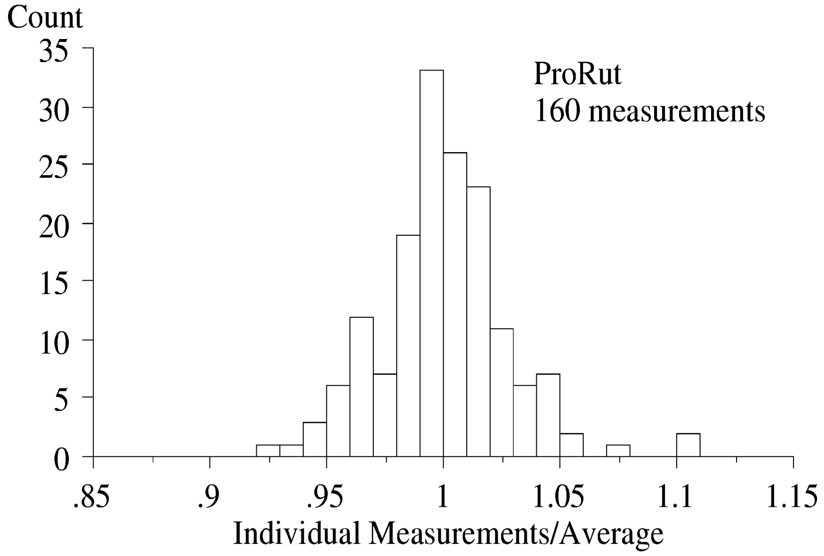

Figure A-1. Repeatability of the ProRut.

Table A-4 summarizes the results. The table provides the standard deviation, the number of measurements within 2 percent of the average, and the number of measurements within 5 percent of the average. The standard deviation is expressed as a percentage. For example, the standard deviation for the histogram in figure A-1 would be listed as 2.7 percent, rather than 0.027.

The number of measurements within 2 percent of the average can be thought of as an indication of a profiler's ability to function as a reference device. Specific definitions aside, a profiler that claims to be "Class 1" should be able to repeat a measurement of IRI within 2 percent on a section 160.9 meters long. On the other hand, only slight deviations in lateral positioning of the measurement can cause changes in IRI larger than that. (*1*) Thus, a profiler may be Class 1 capable, but the combination of profiler, operator, operational procedures, and surface type may not. Of course, the performance of the overall combination of these things is a more informative measure of how a profiler is likely to work in practice. Besides, if a profiler does not include any features that aid a driver in holding a consistent lateral position, why should the resulting variations not reflect on the profiler's probable performance in the field? The same could be said for triggering, detection of bad readings, operating outside the valid speed range for the profiler, etc.

Only two of the profilers measured IRI within 2 percent of the average more than three-fourths of the time. These were both K.J. Law profilers in use at the time in the LTPP study.

The number of measurements within 5 percent of the average is an indication of a profiler's sufficiency for use in network-level profiling. Meeting this requirement means that a profiler can measure a long stretch of road just once (as is usually the case in network monitoring) with confidence that IRI values of 160.9 meters long segments are probably within 5 percent of the value that the profiler would measure in several repeats. Five percent is not very restrictive, but network-level profiling does not require a high level of precision. Besides, the roughness of most roads varies more than 5 percent between network monitoring visits.

Table A-4. Repeatability of profilers in measurement of IRI.

Region	Device	Sensor Type	Number of Meas.	Std. Dev. (%)	Within 2 Percent		Within 5 Percent	
					(Count)	(%)	(Count)	(%)
M	M01	U	80	4.77	26	32.5	59	73.8
	M02	U	158	4.74	61	38.6	126	79.7
	M03	L	116	3.59	62	53.4	99	85.3
	M05	U	160	7.80	48	30.0	95	59.4
	M06	O	200	1.92	162	81.0	194	97.0
N	N03	U	118	6.65	35	29.7	66	55.9
	N04	U	118	6.63	39	33.1	81	68.6
	N06	U	120	5.64	37	30.8	83	69.2
	N07	L	120	4.15	71	59.2	106	88.3
	N08	O	120	3.59	76	63.3	109	90.8
	N09	O	116	3.49	59	50.9	100	86.2
P	P01	L	160	2.72	101	63.1	150	93.8
	P02	U	160	3.76	72	45.0	132	82.5
	P03	U	160	3.87	69	43.1	130	81.3
	P04	L	160	3.80	92	57.5	136	85.0
	P05	O	160	1.86	117	73.1	159	99.4
	P06	U	156	7.46	63	40.4	114	73.1
	P07	O	160	2.57	116	72.5	151	94.4
	P08	L	146	2.37	88	60.3	142	97.3
	P73	U	159	3.84	80	50.3	141	88.7
	P74	U	158	3.00	91	57.6	143	90.5
	P75	U	160	3.20	74	46.3	142	88.8
	P76	U	160	2.28	102	63.8	155	96.9
S	S01	U	130	3.57	71	54.6	112	86.2
	S02	U	80	7.62	23	28.8	44	55.0
	S03	U	80	10.60	12	15.0	33	41.3
	S04	U	77	5.65	30	39.0	53	68.8
	S05	O	94	5.47	68	72.3	87	92.6
	S06	U	79	4.78	37	46.8	66	83.5
	S08	O	154	1.63	131	85.1	152	98.7
	S10	L	116	2.49	63	54.3	113	97.4
	S11	U	80	5.09	31	38.8	63	78.8
	S12	U	80	7.46	25	31.3	49	61.3

M - Mississippi
N - Nevada
P - Pennsylvania
S - South Dakota
O - Optical
U - Ultrasonic
L - Laser

Keep in mind that the level of repeatability in percent, as expressed in this discussion, is tied very closely to the segment length. The variations in IRI would be much lower if the segment length were 1.6 kilometers, rather than 161 meters, and most of these profilers would meet the 5 percent sufficiency requirement just described.

The broad range of performance exhibited by these profilers can be attributed largely to height sensor technology. Table A-5 summarizes the performance of four broad types of profilers: (1) agency-built ultrasonic, (2) commercially built ultrasonic, (3) laser, and (4) optical. Strictly speaking, the normalized roughness values from different regions should not be mixed, because the differences in the test sections gives them different meaning, but they are combined anyway to illustrate the large disparity in performance between the profiler types.

Table A-5. Repeatability of profiler types in measurement of IRI.

Profiler Type	Number of Meas.	Std. Dev. (%)	Within 2 Percent (Count)	(%)	Within 5 Percent (Count)	(%)
Optical	923	2.95	670	72.6	877	95.0
Laser	818	3.23	477	58.3	746	91.2
Ultrasonic, Commercial	2157	5.32	911	42.2	1675	77.7
Ultrasonic, Agency-built	316	6.47	115	36.4	212	67.1

The profilers with ultrasonic sensors were much less repeatable than the others, and do not appear to be acceptable for measuring IRI. Commercially built ultrasonic profilers performed much better than the agency-built profilers, but only a handful of ultrasonic profilers from Pennsylvania exhibited acceptable repeatability for network-level roughness measurement. The profilers with laser sensors were very often within 5 percent of the average, but did not pass the "reference device" test of repeating IRI within 2 percent consistently. Optical profilers performed the best, and were all sufficient for network-level applications.

The difference between the laser and optical profilers is most likely the sensor footprint. The diameter of the footprint of laser sensors ranges from 1 to 5 millimeters. The optical profilers use a rectangular footprint that is 6 mm long and by 150 millimeters wide. This large footprint means that the optical profilers are much less prone to variations caused by short features in the road that a laser profiler might capture in one run but miss in another, such as a narrow crack. The large footprint of the optical height sensor also averages out coarse texture, which is a physical form of anti-alias filtering. The width of the optical height sensor footprint probably also reduces variations in roughness caused by inconsistency in lateral positioning from run to run. With aggressive anti-alias filtering and spike detection, sensors with a very small footprint should be able to perform as well as the optical profilers did in the RPUG experiment.

Ride Number

The same statistics presented in table A-4 were also compiled for the RN. RN is defined as an index computed from profiles in two wheeltracks (*4*). Thus, only profilers that measured two wheeltracks are included in the analysis. In addition, bias in the analysis caused by the nonlinearity of the 0 to 5 scale was avoided by compiling statistics on the Pre-Transform Profile Index used to compute RN, rather than the RN itself. Table A-6 provides the results.

Two optical profilers (P05 and S08) and one laser profiler (P08) stood out as the most repeatable in measuring RN, but some of the others were not even repeatable enough for network-level measurements. About half of the ultrasonic profilers measured RN with good repeatability, but they also measured RN with a significant downward bias.

Table A-6. Repeatability of profilers in measurement of RN.

Region	Device	Sensor Type	Number of Meas.	Std. Dev. (%)	Within 2 Percent (Count)	(%)	Within 5 Percent (Count)	(%)
M	M02	U	79	7.45	25	31.6	51	64.6
	M03	L	58	5.96	32	55.2	45	77.6
	M05	U	80	28.03	8	10.0	24	30.0
	M06	O	100	4.73	62	62.0	90	90.0
N	N03	U	59	10.42	8	13.6	20	33.9
	N04	U	59	6.27	16	27.1	35	59.3
	N06	U	60	6.84	15	25.0	36	60.0
	N07	L	60	3.60	35	58.3	52	86.7
	N08	O	60	12.09	18	30.0	31	51.7
	N09	O	58	8.19	23	39.7	31	53.4
P	P01	L	80	2.79	56	70.0	73	91.3
	P02	U	80	3.67	39	48.8	68	85.0
	P03	U	80	4.23	35	43.8	68	85.0
	P04	L	80	2.87	51	63.8	75	93.8
	P05	O	80	1.76	64	80.0	79	98.8
	P06	U	78	35.64	4	5.1	27	34.6
	P07	O	80	9.55	28	35.0	50	62.5
	P08	L	73	2.36	48	65.8	70	95.9
	P73	U	79	14.19	34	43.0	65	82.3
	P74	U	79	4.00	39	49.4	66	83.5
	P75	U	80	3.59	31	38.8	64	80.0
	P76	U	80	2.61	47	58.8	75	93.8
S	S01	U	65	3.36	37	56.9	57	87.7
	S05	O	47	20.31	26	55.3	36	76.6
	S08	O	77	3.51	58	75.3	75	97.4
	S10	L	58	2.71	37	63.8	51	87.9
	S11	U	40	5.93	19	47.5	30	75.0

M - Mississippi N - Nevada P - Pennsylvania S - South Dakota
O - Optical U - Ultrasonic L - Laser

AGREEMENT WITH THE DIPSTICK

The accuracy of a profiling device is its ability to produce a result that is near the truth without bias. This is an illusive concept. No profiler measures the true profile in the sense that they are all limited to a finite waveband. For example, profilers do not measure topography or texture well, so some part of the true shape of the road is missed. On the other hand, it is possible for a profiler to measure the range of wavelengths of interest for computing IRI or RN correctly. The goal of this section is to present statistics that summarize the accuracy level of the profilers in the 1993 RPUG experiment.

All of the test sections in Mississippi, Pennsylvania, and South Dakota were measured with a Dipstick. The roughness values from these measurements are used as reference values for assessing the “accuracy” of the inertial profilers. All of the measurements covered the same longitudinal range as the Dipstick measurements. Although the lateral position of the profilers was not strictly controlled, paint marks were placed every 7.6 meters along the left wheeltrack of each section to help guide the drivers along a similar path. Since the experiment took place over a few months, changes in roughness of these sections with time may bias the roughness values.

The IRI values computed for all of the measurements in Mississippi, Pennsylvania, and South Dakota were normalized by a reference value from the Dipstick. For example, the ProRut measured eight sections ten times each. The IRI was computed for the left and right wheeltrack in each measurement, for a total of 160 roughness values. The bias between all of these roughness values and the corresponding value from the Dipstick were compiled into a histogram, shown in figure A-2.

The average of the 160 values in the figure is 9.4, which means that the ProRut measured IRI an average of 9.4 percent higher than the Dipstick. This is an overall estimate of the bias between the ProRut and the Dipstick. The average bias level represents the accuracy of the ProRut if the Dipstick is accepted as a reference. The RMS error was 12.3 percent. The RMS error penalizes a profiler for bias and scatter, so it delineates a combination of the accuracy and repeatability problems in a profiler. All profilers will have some level of RMS error. For network-level applications, a combination of no bias and an RMS error under 5 percent is preferred.

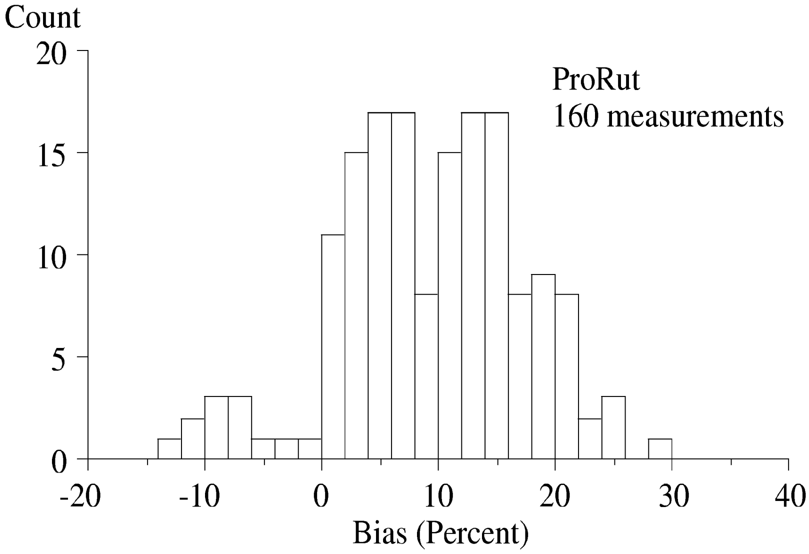

Figure A-2. Bias in IRI by the ProRut.

Bias errors can exist for several reasons: aliasing errors caused by narrow cracks or coarse surface texture, spikes in the sensor signals caused by the environment, variations in lateral tracking that consistently place a profiler on a path other than the one measured by the reference device, or changes in the road surface between the day of the reference measurement and the day of the other tests. The RMS error should include all of the factors that confound profiler measurement, including the factors just listed and everything that degrades the repeatability of a set of measurements.

IRI values from all of the profilers in Mississippi, Pennsylvania, and South Dakota were compared to Dipstick values as a means of characterizing each profiler's bias and RMS error level. The results are listed in table A-7. The results should not be interpreted too precisely, since not every profiler made the same set of measurements. Not all of the profilers within a region measured all of the sections exactly ten times. Some profilers, usually the South Dakota type, measured only the left wheeltrack. Each region had a unique set of sections, so only comparisons of major trends should be made across all of the regions. Nevertheless, some of the trends are so strong that they are meaningful.

Very few devices stood out as agreeing with the Dipstick measurements very well. The few promising numbers in table A-7 are listed in bold. The bias and RMS error of these devices was heavily linked to the sensor type. Figures A-3 through A-6 show the histograms for all measurements by four broad types of profiler: (1) agency-built ultrasonic, (2) commercially built ultrasonic, (3) laser, and (4) optical. Table A-8 also provides summary statistics. All of the histograms are shown on the same scale for comparison. The optical profilers had the lowest bias and RMS error, followed by the laser profilers. As described in the section on repeatability, the large footprint of the optical sensors is probably the reason optical profilers in the RPUG study generally agreed with the Dipstick more closely than laser profilers.

Table A-7. Agreement to Dipstick of profilers in measurement of IRI.

Region	Device	Sensor Type	Number of Meas.	Bias (%)	RMS Error (%)	Within 5 Percent	
						(Count)	(%)
M	M01	U	80	11.4	14.8	19	23.8
	M02	U	158	21.3	26.9	21	13.3
	M03	L	116	**5.1**	10.8	38	32.8
	M05	U	160	9.3	15.9	46	28.8
	M06	O	200	**4.7**	**8.4**	77	38.5
P	P01	L	160	9.4	12.3	36	22.5
	P02	U	160	30.1	34.8	0	0.0
	P03	U	160	27.3	32.3	0	0.0
	P04	L	160	12.0	16.3	37	23.1
	P05	O	160	11.0	14.9	27	16.9
	P06	U	156	32.4	39.0	0	0.0
	P07	O	160	11.3	13.3	19	11.9
	P08	L	146	9.5	11.5	40	27.4
	P73	U	159	25.7	31.7	4	2.5
	P74	U	158	23.7	27.9	5	3.2
	P75	U	160	21.1	26.8	13	8.1
	P76	U	160	22.6	28.3	3	1.9
S	S01	U	130	44.8	62.3	23	17.7
	S02	U	80	18.9	29.2	24	30.0
	S03	U	80	42.4	68.5	27	33.8
	S04	U	77	51.1	70.4	18	23.4
	S05	O	94	**-0.3**	**7.6**	70	**74.5**
	S06	U	79	50.6	71.7	16	20.3
	S08	O	154	**2.9**	**7.3**	83	**53.9**
	S10	L	116	13.7	19.1	33	28.4
	S11	U	80	36.0	51.0	8	10.0
	S12	U	80	51.8	77.3	19	23.8

M - Mississippi N - Nevada P - Pennsylvania S - South Dakota
O - Optical U - Ultrasonic L - Laser

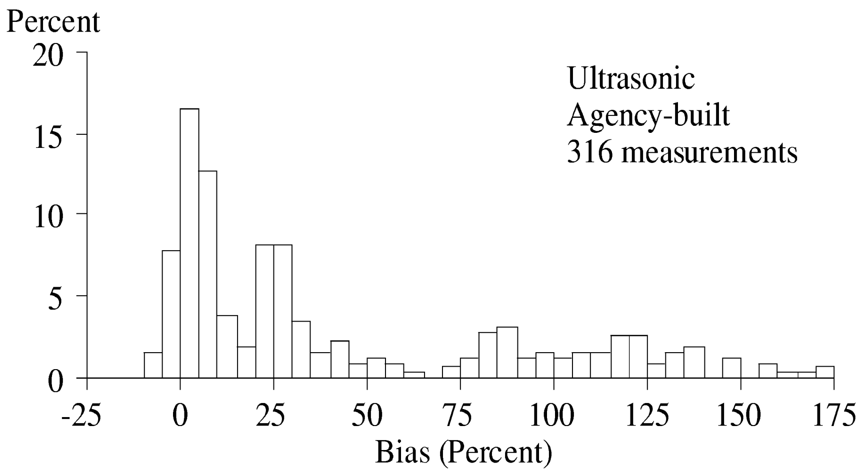

Figure A-3. Bias in agency-built ultrasonic profilers from the RPUG.

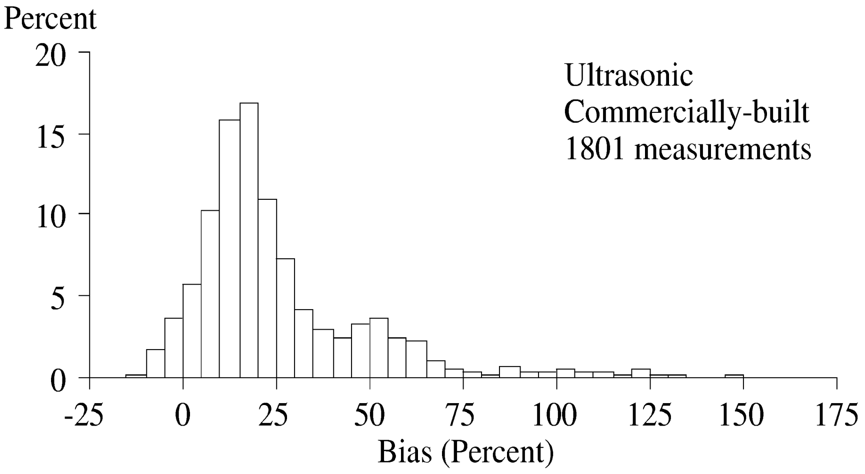

Figure A-4. Bias in commercial ultrasonic profilers from the RPUG.

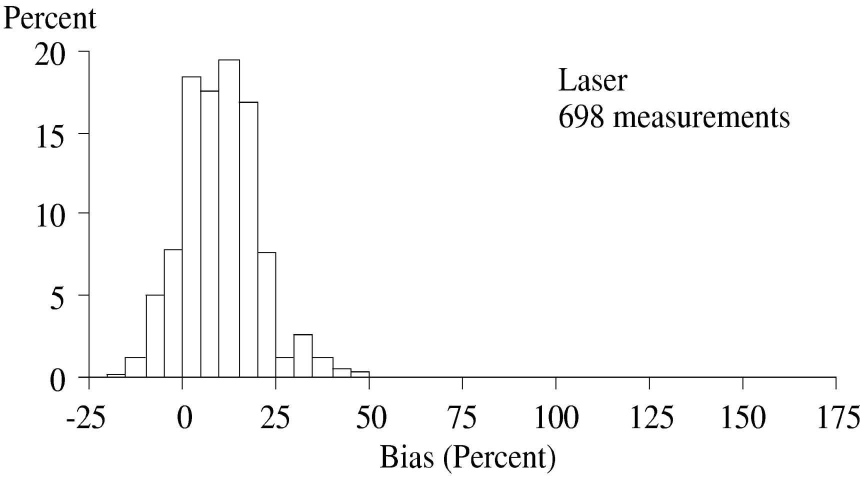

Figure A-5. Bias in laser profilers from the RPUG.

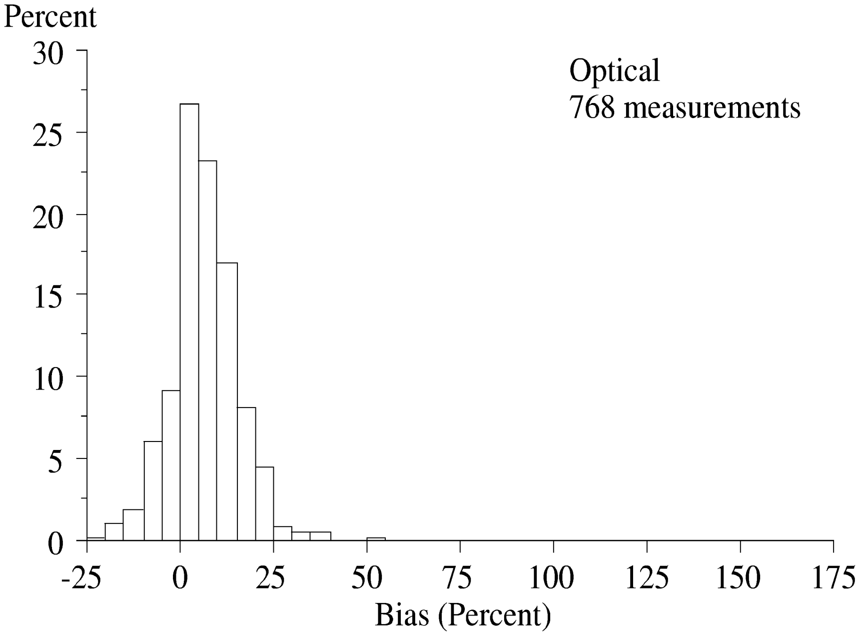

Figure A-6. Bias in optical profilers from the RPUG.

The scatter and bias of the laser and optical profilers compared to the Dipstick measurements are most likely caused by lateral tracking variations, sensing of short features that the Dipstick ignores, the lack of aggressive measures to avoid aliasing errors, and problems inherent in using noncontact sensors in an uncontrolled environment at high speed.

The ultrasonic profilers, both agency-built and commercial, measured IRI with huge bias and scatter. In contrast to the laser and optical sensors, ultrasonic sensors are not sufficient for the job of measuring IRI. Some of the commercial ultrasonic profilers performed well on most sections, but horribly on sections with coarse surface texture. This is why the histograms in figure A-3 and A-4 extend so far to the right. If IRI values are to be compared from agency to agency or year to year, ultrasonic sensors must be replaced.

Table A-8. Agreement to the Dipstick of profiler types in IRI measurement.

Profiler Type	Number of Meas.	Bias (%)	RMS Error (%)	Within 5 Percent (Count)	(%)
Optical	768	6.4	10.9	276	35.9
Laser	698	10.0	14.2	184	26.4
Ultrasonic, Commercial	1801	26.1	36.4	169	9.4
Ultrasonic, Agency-built	316	43.0	65.0	77	24.4

SURFACE TEXTURE

Coarse surface macrotexture has the potential to cause an upward bias in roughness. For example, on a pavement with a fresh chip seal height sensors with a small footprint may detect the top of a piece of protruding aggregate in one sample and miss the aggregate in another. If the sample interval is too large or a profiler operates without anti-aliasing filters, the texture could erroneously appear in the final profile as deviations with a long enough wavelength to affect the IRI or RN. Laser sensors sample fast enough to allow surface texture to be recognized and averaged out using anti-alias filters. Optical height sensors have a footprint so large that coarse texture is probably averaged out.

Ultrasonic sensors have a footprint that is 50 to 100 millimeters in diameter. This footprint is large enough to average out texture, but ultrasonic height sensors do not work this way. They register a reading as soon as the reflected acoustic wave is first detected, so they actually detect the highest point within the footprint. There is no way to average these deviations out, because a reading can only be taken about 3 or 4 times per meter at highway speed. This causes a major bias in roughness measurement on roads with coarse texture.

For example, sections 3 and 4 in Pennsylvania were asphalt surfaces with chip seals. These two sections had very coarse surface texture compared to the others. Table A-9 lists the texture depth from ASTM sand patch tests of sections 1 through 8 in Pennsylvania. All of the profilers with ultrasonic sensors measured IRI with an extreme bias on sections 3 and 4. Figure A-7 shows a histogram of all of the measurements by ultrasonic profilers in Pennsylvania. There is a group of measurements with a bias around 20 percent, but a second, smaller group with a bias of about 55 percent. The group with a bias around 55 percent is mostly measurements of sections 3 and 4.

Table A-9. Bias in profilers by section in Pennsylvania.

Surface Type	AC Without Chip Seal		AC With Chip Seal		Portland Cement Concrete			
Section Number	1	2	3	4	5	6	7	8
Macrotexture Depth (mm)	0.65	0.53	1.78	1.39	0.66	0.58	0.53	0.69
Bias, Optical Profilers (%)	16.5	-1.6	6.1	8.1	9.6	12.4	19.5	18.3
Bias, Laser Profilers (%)	15.3	5.9	4.8	5.0	3.2	11.6	16.8	19.9
Bias, Ultrasonic Profilers (%)	18.3	18.7	54.5	46.1	22.1	12.3	16.2	20.3

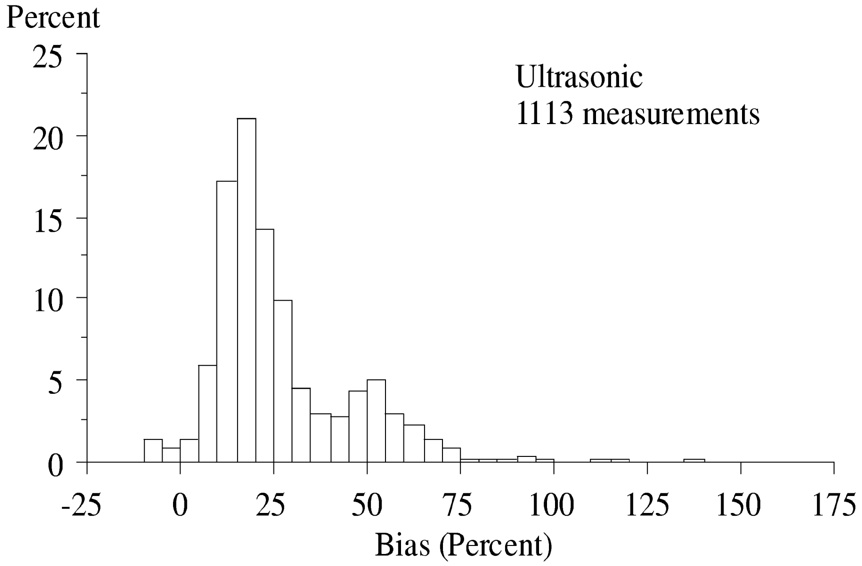

Figure A-7. Bias in ultrasonic profilers from the RPUG in Pennsylvania.

Table A-9 summarizes the bias in IRI compared to the Dipstick on each section in Pennsylvania by height sensor type. The results for the other six sections are also listed for comparison. The ultrasonic profilers had extreme difficulty with sections 3 and 4. In fact, none of their measurements agree with the Dipstick within 5 percent. Their performance is much better on the other sections, but still not acceptable.

The profilers with laser and optical sensors actually agree with the Dipstick more closely on sections 3 and 4 than the others. Coarse macrotexture of the kind typical of a chip seal apparently does not cause systematic errors in these profilers. However, all of the laser and optical profilers showed the highest bias on sections 7 and 8. A likely explanation for the elevated roughness is that the laser and optical sensors registered roughness at opened joints (or cracks) that the Dipstick did not. This may also explain the bias in IRI on section 1, which was very rough and probably included narrow forms of distress like cracks that the Dipstick would ignore.

Table A-10 summarizes the bias in IRI compared to the Dipstick on each section in South Dakota by height sensor type. Sections 2, 3, and 4 in South Dakota all had chip seals, and all have high values of macrotexture depth. Profilers with ultrasonic sensors exhibited an extreme bias on these sections. The optical profilers agreed reasonably well with the Dipstick on all of the sections, but the laser profiler did not. Only one laser profiler participated in the study in South Dakota. Most of the bias in its measurements come from large upward spikes that are not caused by coarse texture.

Table A-10. Bias in profilers by section in South Dakota.

Surface Type	Asphalt Concrete				Portland Cement Concrete			
Section Num.	1	2	3	4	5	6	7	8
Macrotexture Depth (mm)	1.08	1.42	1.31	1.33	0.78	0.33	0.67	0.38
Bias, Optical Profilers (%)	-5.3	-1.0	-1.2	2.1	9.3	3.4	4.2	3.5
Bias, Laser Profilers (%)	5.6	20.3	10.6	28.2	12.9	-1.5	6.7	—
Bias, Ultrasonic Profilers (%)	4.3	104.5	59.7	107.6	17.2	5.9	16.9	11.8

OPERATING SPEED

Most of the profilers listed in table A-2 performed ten or more measurements of each section: five measurements at a speed near 80 kph (called higher speed repeats) and five more at a speed near 64 kph (called lower speed repeats). In a few isolated cases, measurements were made at speeds of 72 kph and 56 kph instead. This matrix of runs was intended to reveal any bias in roughness measurement caused by modest variations in operating speed. Tables A-11 through A-14 list the ratio of the Mean Roughness Index (MRI) measured at the higher speed to the MRI measured at the lower speed. (MRI is the average of the IRI from the left and right wheeltrack.) Each value in the tables represents the average of the higher speed repeats divided by the average of the lower speed repeats on a particular section by a particular profiler. In most cases, exactly five measurements of each section at each speed were made. A value is only listed if at least four measurements at each speed were available. A table is provided for each region, since each region used a distinct set of sections. (In other words, section 1 in South Dakota is not the same as section 1 in Pennsylvania, etc.)

Table A-11. Speed sensitivity of profilers in Mississippi.

	Average MRI at high speed/Average MRI at low speed							
	Asphalt Sections				Concrete Sections			
Device	1	2	3	4	5	6	7	8
M02	1.06	1.08	1.05	1.01	1.06	0.97	0.97	1.01
M03	—	—	0.97	—	1.02	1.04	—	0.99
M05	1.03	0.96	1.01	1.03	1.02	1.00	1.05	1.14
M06	1.02	1.01	0.99	1.03	1.00	0.99	1.01	1.01

Table A-12. Speed sensitivity of profilers in Nevada.

	Average MRI at high speed/Average MRI at low speed					
	Asphalt Sections			Concrete Sections		
Device	1	2	3	4	5	6
N03	1.06	1.03	1.06	1.12	1.10	1.01
N04	1.08	1.07	1.15	1.01	1.04	1.01
N06	1.11	1.11	1.03	1.01	1.00	0.99
N07	0.98	0.97	0.96	1.01	0.99	0.99
N08	1.00	1.01	0.97	1.05	1.02	1.00
N09	0.97	1.01	1.03	1.07	0.97	1.00

Table A-13. Speed sensitivity of profilers in Pennsylvania.

	Average MRI at high speed/Average MRI at low speed							
	Asphalt Sections				Concrete Sections			
Device	1	2	3	4	5	6	7	8
P01	1.00	1.01	0.99	0.98	0.99	0.97	1.05	0.99
P02	1.04	1.06	0.96	**1.12**	1.04	0.98	1.02	1.00
P03	1.05	0.98	0.95	**1.08**	1.05	0.99	0.99	1.03
P04	0.99	0.92	0.98	0.93	0.97	1.00	0.98	0.95
P05	1.05	1.00	1.00	1.00	1.02	1.03	1.04	1.03
P06	1.02	0.97	1.02	**1.26**	1.03	1.02	1.04	0.98
P07	1.00	1.07	1.01	1.00	1.00	0.99	0.98	1.01
P08	1.04	1.05	1.02	0.94	1.01	1.02	1.01	1.02
P73	0.99	1.01	0.98	**1.12**	0.98	0.97	1.00	1.01
P74	1.00	1.00	0.99	**1.08**	1.01	0.99	0.98	1.00
P75	1.02	1.03	0.99	**1.08**	0.99	0.98	0.98	0.99
P76	0.99	0.98	1.00	**1.03**	1.00	1.00	1.00	0.98

Table A-14. Speed sensitivity of profilers in South Dakota.

	Average MRI at high speed/Average MRI at low speed							
	Asphalt Sections				Concrete Sections			
Device	1	2	3	4	5	6	7	8
S01	—	0.98	1.05	1.02	1.02	—	1.01	—
S08	1.01	0.99	1.01	1.02	1.01	0.99	1.02	1.00
S10	1.01	0.99	0.99	0.99	0.98	—	—	—

Table A-15 summarizes the results for each profiler organized by sensor type. The table lists the average of the values given for all sections in tables A-11 through A-14 and the minimum and maximum. Keep in mind that profilers from different regions encountered different sections and not all profilers covered all sections, so only major trends are likely to have significant implications about the effect of operating speed. Very few of these devices showed an overall bias with operating speed that was more significant than the scatter they exhibit within a given speed. (That is, the average listed in table A-15 rarely accounts for most of the standard deviation listed in table A-4, and the scatter within repeats at the two speeds overlap each other.)

Table A-15. Summary of trends in MRI with operating speed.

Sensor Type	Device	Average	Minimum	Maximum
Laser	M03	1.00	0.97	1.04
	N07	0.98	0.96	1.01
	P01	1.00	0.97	1.05
	P04	0.97	0.92	1.00
	P08	1.01	0.94	1.05
	S10	0.99	0.98	1.01
Optical	M06	1.01	0.99	1.03
	N08	1.01	0.97	1.05
	N09	1.01	0.97	1.07
	P05	1.02	1.00	1.05
	P07	1.01	0.98	1.07
	S08	1.01	0.99	1.02
Ultrasonic	M02	1.03	0.97	1.08
	M05	1.03	0.96	1.14
	N03	1.06	1.01	1.12
	N04	1.06	1.01	1.15
	N06	1.04	0.99	1.11
	P02	1.03	0.96	1.12
	P03	1.01	0.95	1.08
	P06	1.04	0.97	1.26
	P73	1.01	0.98	1.12
	P74	1.01	0.98	1.08
	P75	1.01	0.98	1.08
	P76	1.00	0.98	1.03
	S01	1.02	0.98	1.05

In general, the profilers with ultrasonic sensors measured higher MRI values at the higher speed. This is because a sensor error that drives up the roughness is more likely to occur at higher speed. This explains why the averages in table A-15 for ultrasonic sensors are all greater than one, although the trend is weak. One example that stands out (if for no other reason, because they are in bold type) is that all of the profilers with ultrasonic sensors measured MRI values that were significantly higher at the higher speed on Pennsylvania section 4. (See table A-14.) This is not the section with the highest macrotexture depth, but its texture did seem most problematic to profilers with ultrasonic sensors.

A few other weak trends exist with speed, but most of them are not systematic. In most of the cases of extreme values in tables A-11 through A-14, a single anomalous value from one measurement skewed the average for one of the speeds, rather than a systematic bias in all repeats. The only other case of a systematic bias with speed was exhibited by profiler P04. It produced lower MRI at the higher speed on all sections. The explanation for this is not known.

Table A-16 shows a summary for trends in RN with operating speed compiled in the same manner as MRI in table A-15. Very few of the profilers are speed sensitive. A few of the ultrasonic profilers appeared speed sensitive on sections of coarse macrotexture, but the RN values were so far off at both speeds that the trend is not worth examination.

Table A-16. Summary of trends in RN with operating speed.

Sensor Type	Device	Average	Minimum	Maximum
Laser	M03	1.01	0.99	1.06
	N07	1.00	1.00	1.01
	P01	0.99	0.96	1.00
	P04	1.00	0.96	1.02
	P08	0.99	0.97	1.01
	S10	1.02	0.99	1.04
Optical	M06	1.01	0.98	1.09
	N08	0.98	0.89	1.10
	N09	0.95	0.90	1.00
	P05	0.99	0.97	1.00
	P07	1.00	0.95	1.09
	S08	1.01	1.00	1.02
Ultrasonic	M02	0.99	0.91	1.05
	M05	1.01	0.85	1.13
	N03	0.93	0.88	1.00
	N04	0.98	0.93	1.04
	N06	0.97	0.92	1.00
	P02	1.00	0.96	1.04
	P03	0.99	0.96	1.02
	P06	0.87	0.50	1.03
	P73	0.98	0.73	1.04
	P74	1.00	0.97	1.02
	P75	1.00	0.96	1.05
	P76	1.00	0.98	1.02
	S01	0.98	0.92	1.00

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3. Huft, D. L. “Description and Evaluation of the South Dakota Road Profiler.” Federal Highway Administration, *FHWA-DP-89-072-002* (1989) 159 p.
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Appendix B: Cross Correlation Results, 1993 RPUG Study

This appendix lists the results of cross correlation analysis performed on all of the profile measurements from the 1993 RPUG study. Details of the study are provided in Appendix A, and are documented elsewhere. (*1*) Ratings of agreement between profilers and repeatability of each device are listed for four wavebands:

1. IRI Filter: The output of the IRI algorithm. This is a slope profile with frequency weighting determined by the quarter car filter using the Golden Car parameters.
2. Long Wavelengths: The slope profile, passed through a four-pole Butterworth filter with cutoff wavelengths of 8 and 40 meters.
3. Medium Wavelengths: The slope profile, passed through a four-pole Butterworth filter with cutoff wavelengths of 1.6 and 8 meters.
4. Short Wavelengths: The slope profile, passed through a four-pole Butterworth filter with cutoff wavelengths of 0.32 and 1.6 meters.

Cross correlation of IRI filter output emphasizes content in the profiles that is relevant to the accumulation of IRI. The other three filters were included to help diagnose the source of disagreement between profiles by isolating each waveband. All of the cross correlation values were calculated after longitudinal distance measurement offset was removed, so the profiles cover the same pavement. On the other hand, linear distance measurement error was not corrected. Errors in distance measurement as small as a percent reduce correlation, particularly in the short wavelength range.

Two hundred forty tables of cross correlation values are provided, covering each type of filter and sixty individual wheeltracks (up to eight sites in four regions, left and right). Table B–1 lists all of the devices covered by the analysis and the number of measurements they made on each site. Tables B–2 through B–241 cover all possible combinations of device on all sites for all four wavebands.

For each combination of filter and site, all of the measurements from a given device are compared to all of the measurements from the other. The result is an average correlation level that constitutes a single entry in one table. Each table entry provides the average correlation level for every combination of measurements by the appropriate pair of devices. For example, on the left wheeltrack of Mississippi site 1, profiler M01 and M02 each made ten profile measurements. Thus, one hundred comparisons are possible, and the table entry is the average of one hundred cross correlation values.

Note that the two devices are compared twice. In the first comparison, M01 is deemed the “reference device,” and the measurements from device M02 are compared to them. This means that the sample interval from device M01 is retained, and the measurements from device M02 are interpolated to obtain a one-to-one correspondence. In the second comparison, profiles from device M02 are treated as the reference, and profiles from device M01 are interpolated to match them. The two values are usually similar, except when the short wavelengths are compared. This is because the short wavelengths are affected most by sample interval.

Not all entrees are the average of one hundred values. When fewer measurements were made by one of the devices, it reduced the number of possible comparisons. Several devices did not measure the right wheeltrack, so they are omitted from the appropriate tables.

The individual table entrees provide a rating of the ability of one device to reproduce the measurements of another in a given waveband. Agreement to the Dipstick was thought of as a profiler's "accuracy" at the time of the experiment. Although the Dipstick measurements can not be considered a perfect reflection of the true profile, it is the only reference device that participated in the study. The Dipstick only measured each wheeltrack once. Thus, the majority of listings for agreement to the Dipstick are the average of ten correlation values.

The diagonal entrees in the tables provide a rating of repeatability, because they are the average of the correlation levels that result for all combinations of repeat measurements by the same device. (Ten repeat measurements yield forty-five possible comparisons, so these entrees are usually the average of forty-five correlation values.) No values are listed for repeatability of the Dipstick, because no repeat measurements were made.

Note also that correlation level is expressed on a scale that ranges from -100 to 100, rather than -1 to 1. This is done for ease of interpretation. There are several reasons why the correlation levels are lower than 100. Differences in height sensor technology, sample interval, and profile computation method degrade the level of agreement between devices. Most devices measured the site at different times and on different dates. The correlation levels are therefore affected by changes in roughness with time, including the trend toward higher roughness as the pavement ages, and cyclic changes caused by the weather and climate. Agreement is, of course, also degraded by measurement error. Agreement and repeatability are both degraded by lateral wander of the profilers. The RPUG study did include special provisions to help high-speed profilers maintain a consistent lateral position during the measurements, but this can never be completely controlled. Gentle lateral wander usually only affects measurement of short wavelengths.

Several relevant trends appear in these data that may have helped diagnose some of the measurement problems discovered in the 1993 RPUG study. For example, the lack of reciprocity in some of the cross correlation values suggests that the sample interval was insufficient for the waveband of interest. (Reciprocity is obtained when comparisons of one device to another are not sensitive to which device is chosen as a correlation reference. The choice of a reference is important because the other device's profile is interpolated to match its sample interval.) In particular, the lack of reciprocity observed when the IRI filter is used in the cross correlation procedure is evidence that the sample interval was not sufficient for computation of the IRI. The extremely poor correlation in the short wavelength range also indicates that the shorter sample interval was needed, or that filtering was not done properly for very short wavelengths. Indeed, the profilers with ultrasonic sensors used no low-pass filtering at all.

Further, the diversity in cross correlation level of the same profiler on different sites provides insight into which sites challenge each profiler the most. The most obvious example of this was the degraded correlation in the medium wavelengths, short wavelengths and IRI filter on coarse textured sites by profilers with ultrasonic sensors.

Table B-1. Coverage of each site in the 1993 RPUG experiment.

Region	Inst. #	Sensor Type	Tracks	Number of Measurements at Each Site								
				All	1	2	3	4	5	6	7	8
M	MDS	I	B	8	1	1	1	1	1	1	1	1
	M01	U	L	80	10	10	10	10	10	10	10	10
	M02	U	B	79	10	10	10	10	10	10	9	10
	M03	L	B	58	8	4	9	8	10	9	0	10
	M05	U	B	80	10	10	10	10	10	10	10	10
	M06	O	B	100	10	10	14	16	12	14	10	14
N	NDS	I	B	8	1	1	1	1	1	1	—	—
	N03	U	B	59	10	10	10	10	9	10	—	—
	N04	U	B	60	10	10	10	10	10	10	—	—
	N06	U	B	60	10	10	10	10	10	10	—	—
	N07	L	B	61	10	10	10	10	11	10	—	—
	N08	O	B	60	10	10	10	10	10	10	—	—
	N09	O	B	58	10	10	10	10	8	10	—	—
P	PDS	I	B	8	1	1	1	1	1	1	1	1
	P01	L	B	80	10	10	10	10	10	10	10	10
	P02	U	B	80	10	10	10	10	10	10	10	10
	P03	U	B	80	10	10	10	10	10	10	10	10
	P04	L	B	80	10	10	10	10	10	10	10	10
	P05	O	B	80	10	10	10	10	10	10	10	10
	P06	U	B	78	9	10	10	10	10	10	10	9
	P07	O	B	80	10	10	10	10	10	10	10	10
	P08	L	B	74	9	8	9	10	9	10	9	10
	P73	U	B	80	10	10	10	10	10	10	10	10
	P74	U	B	79	10	10	10	10	10	10	9	10
	P75	U	B	80	10	10	10	10	10	10	10	10
	P76	U	B	80	10	10	10	10	10	10	10	10
S	SDS	I	B	8	1	1	1	1	1	1	1	1
	S01	U	B	65	5	10	10	10	10	5	10	5
	S02	U	L	80	10	10	10	10	10	10	10	10
	S03	U	L	80	10	10	10	10	10	10	10	10
	S04	U	L	77	10	10	10	10	7	10	10	10
	S05	O	B	47	6	8	4	7	2	6	10	4
	S06	U	L	79	9	10	10	10	10	10	10	10
	S08	O	B	77	10	9	10	10	10	9	9	10
	S10	L	B	58	10	10	10	10	10	4	4	0
	S11	U	B	40	5	5	5	5	5	5	5	5
	S12	U	L	80	10	10	10	10	10	10	10	10

M - Mississippi	N - Nevada	P - Pennsylvania	S - South Dakota
I - Inclinometer	O - Optical	U - Ultrasonic	L - Laser
L - Left	B - Both (Left and Right)		

Table B–2. Mississippi Site 1 Left, IRI Filter.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	78	54	69	65	69	70
02	57	81	52	48	68	65
03	71	52	79	67	70	76
05	67	47	67	61	66	68
06	72	69	70	66	88	83
DS	74	65	78	67	84	—

Table B–3. Mississippi Site 1 Left, Long Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	95	83	75	86	95	81
02	84	97	88	76	86	90
03	76	88	97	73	78	95
05	85	75	73	85	86	76
06	95	85	78	87	**99**	84
DS	81	90	95	76	84	—

Table B–4. Mississippi Site 1 Left, Medium Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	71	39	60	52	57	60
02	45	71	38	33	55	50
03	64	38	73	60	63	67
05	59	34	61	53	57	61
06	62	56	63	56	83	77
DS	69	51	68	58	79	—

Table B–5. Mississippi Site 1 Left, Short Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	45	9	11	8	7	15
02	16	39	8	7	8	9
03	21	13	42	23	12	26
05	21	11	18	19	11	18
06	22	15	13	12	50	29
DS	31	12	17	14	24	—

Table B–6. Mississippi Site 1 Right, IRI Filter.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	80	51	51	65	60
03	49	90	78	73	79
05	48	77	75	76	69
06	61	72	74	**95**	72
DS	58	83	74	76	—

Table B–7. Mississippi Site 1 Right, Long Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	97	85	71	84	87
03	85	98	72	79	96
05	70	72	92	82	72
06	83	79	83	99	82
DS	86	96	73	82	—

Table B–8. Mississippi Site 1 Right, Medium Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	73	43	42	56	50
03	39	88	75	67	71
05	39	75	68	68	64
06	49	65	61	93	65
DS	47	78	70	72	—

Table B–9. Mississippi Site 1 Right, Short Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	42	11	9	10	7
03	11	63	28	14	23
05	10	31	21	17	18
06	10	15	14	68	19
DS	9	33	21	29	—

Table B–10. Mississippi Site 2 Left, IRI Filter.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	71	34	57	62	75	64
02	37	49	34	32	42	36
03	57	32	71	56	61	65
05	62	30	56	62	65	63
06	75	39	60	65	92	72
DS	61	33	64	60	71	—

Table B–11. Mississippi Site 2 Left, Long Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	98	78	72	94	92	74
02	78	95	87	76	86	92
03	71	87	99	70	79	91
05	94	76	70	93	88	73
06	92	86	79	88	99	83
DS	74	92	91	73	83	—

Table B–12. Mississippi Site 2 Left, Medium Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	54	16	45	39	60	51
02	19	33	15	15	24	18
03	46	13	48	43	49	45
05	42	13	42	43	44	47
06	60	21	47	41	82	60
DS	50	15	44	40	58	—

Table B–13. Mississippi Site 2 Left, Short Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	33	3	7	4	8	8
02	6	19	8	7	8	8
03	14	7	14	11	10	12
05	13	6	11	16	9	8
06	28	6	8	6	33	10
DS	20	5	9	6	12	—

Table B–14. Mississippi Site 2 Right, IRI Filter.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	55	44	40	48	50
03	42	90	69	75	81
05	38	71	68	73	67
06	46	75	70	**94**	76
DS	47	86	69	80	—

Table B–15. Mississippi Site 2 Right, Long Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	95	92	71	84	91
03	92	99	69	80	94
05	71	69	95	85	70
06	84	81	85	99	83
DS	91	94	70	83	—

Table B–16. Mississippi Site 2 Right, Medium Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	31	22	20	27	27
03	20	81	56	69	69
05	18	63	54	54	59
06	24	70	47	87	64
DS	23	78	53	73	—

Table B–17. Mississippi Site 2 Right, Short Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	14	8	7	9	10
03	6	36	15	11	19
05	7	25	18	10	14
06	6	11	6	50	19
DS	8	27	10	23	—

Table B–18. Mississippi Site 3 Left, IRI Filter.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	52	31	47	31	43	55
02	34	44	28	29	33	37
03	47	29	78	48	67	62
05	34	30	49	47	50	46
06	49	35	69	51	82	57
DS	50	33	57	42	54	—

Table B–19. Mississippi Site 3 Left, Long Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	94	69	54	78	91	64
02	70	94	85	62	74	87
03	55	85	92	51	59	87
05	78	62	51	75	79	57
06	92	74	60	79	99	69
DS	65	86	87	57	69	—

Table B–20. Mississippi Site 3 Left, Medium Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	47	20	42	24	33	51
02	26	33	20	22	24	28
03	43	21	76	43	61	54
05	28	24	45	43	42	40
06	40	27	63	44	79	49
DS	44	22	49	35	45	—

Table B–21. Mississippi Site 3 Left, Short Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	31	4	11	5	5	12
02	8	17	8	8	7	13
03	20	8	63	21	28	27
05	13	9	19	20	13	26
06	17	12	35	21	64	30
DS	27	7	20	16	15	—

Table B–22. Mississippi Site 3 Right, IRI Filter.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	55	31	32	39	33
03	28	76	38	64	65
05	30	40	39	53	37
06	36	65	52	89	49
DS	30	62	34	47	—

Table B–23. Mississippi Site 3 Right, Long Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	91	84	57	65	79
03	83	97	54	61	92
05	57	54	76	78	55
06	65	61	78	99	64
DS	79	92	55	64	—

Table B–24. Mississippi Site 3 Right, Medium Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	45	23	25	32	25
03	19	72	32	58	59
05	22	34	33	46	30
06	27	60	44	86	46
DS	20	55	27	42	—

Table B–25. Mississippi Site 3 Right, Short Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	22	8	9	12	9
03	5	62	15	25	32
05	8	17	12	17	14
06	9	27	14	68	33
DS	5	25	8	19	—

Table B–26. Mississippi Site 4 Left, IRI Filter.

Correlation Reference	Correlated Device 01	02	03	05	06	DS
01	53	35	41	32	56	58
02	38	60	27	36	60	51
03	42	28	74	48	58	47
05	36	39	51	57	52	38
06	56	56	53	47	90	73
DS	52	45	46	34	71	—

Table B–27. Mississippi Site 4 Left, Long Wavelengths.

Correlation Reference	Correlated Device 01	02	03	05	06	DS
01	90	60	48	82	87	44
02	60	95	59	60	68	91
03	48	58	73	51	56	53
05	82	60	51	88	84	46
06	87	68	56	85	98	51
DS	45	91	53	46	51	—

Table B–28. Mississippi Site 4 Left, Medium Wavelengths.

Correlation Reference	Correlated Device 01	02	03	05	06	DS
01	46	25	41	24	48	52
02	30	50	26	28	54	43
03	43	27	72	44	55	46
05	30	32	49	49	46	32
06	48	45	52	39	88	71
DS	46	34	43	27	69	—

Table B–29. Mississippi Site 4 Left, Short Wavelengths.

Correlation Reference	Correlated Device 01	02	03	05	06	DS
01	28	4	9	4	8	10
02	9	28	8	8	17	10
03	16	10	42	21	25	21
05	12	13	23	25	23	17
06	22	13	20	12	77	30
DS	24	7	13	8	38	—

Table B–30. Mississippi Site 4 Right, IRI Filter.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	66	28	40	54	52
03	26	84	48	56	68
05	36	47	47	63	52
06	49	54	59	**95**	73
DS	46	67	51	77	—

Table B–31. Mississippi Site 4 Right, Long Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	95	79	62	74	91
03	80	91	59	67	74
05	63	59	88	82	46
06	75	68	82	99	55
DS	91	74	47	55	—

Table B–32. Mississippi Site 4 Right, Medium Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	59	24	33	47	45
03	20	82	41	52	63
05	29	44	39	54	46
06	39	50	47	94	65
DS	37	63	42	72	—

Table B–33. Mississippi Site 4 Right, Short Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	30	9	7	15	8
03	7	52	11	16	23
05	9	17	14	19	15
06	10	13	10	84	25
DS	6	19	8	31	—

Table B–34. Mississippi Site 5 Left, IRI Filter.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	87	49	78	76	74	78
02	55	82	53	39	76	64
03	82	50	**94**	82	80	86
05	80	37	82	87	68	76
06	78	70	79	66	**97**	86
DS	80	58	84	73	86	—

Table B–35. Mississippi Site 5 Left, Long Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	95	79	74	81	94	81
02	79	96	80	67	81	83
03	74	80	98	71	78	96
05	81	66	71	88	83	75
06	93	81	78	83	99	85
DS	81	83	95	76	85	—

Table B–36. Mississippi Site 5 Left, Medium Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	85	39	74	68	66	70
02	46	77	42	30	69	54
03	79	42	93	79	76	81
05	77	29	79	84	60	71
06	73	64	73	56	97	81
DS	79	49	79	66	84	—

Table B–37. Mississippi Site 5 Left, Short Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	69	7	26	17	13	20
02	12	48	9	9	17	14
03	46	11	78	38	22	35
05	41	11	46	61	12	32
06	32	19	22	9	85	35
DS	36	15	45	27	47	—

Table B–38. Mississippi Site 5 Right, IRI Filter.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	84	55	43	73	57
03	52	**97**	86	81	79
05	40	85	89	72	70
06	67	80	69	**97**	81
DS	52	76	66	80	—

Table B–39. Mississippi Site 5 Right, Long Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	96	82	69	79	77
03	81	98	74	81	90
05	68	74	93	86	80
06	79	80	87	98	83
DS	76	90	80	82	—

Table B–40. Mississippi Site 5 Right, Medium Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	79	49	37	70	52
03	44	96	82	78	76
05	34	84	87	66	65
06	61	76	60	97	79
DS	45	72	59	78	—

Table B–41. Mississippi Site 5 Right, Short Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	52	8	9	19	17
03	11	86	41	24	40
05	10	55	67	13	24
06	20	24	10	89	37
DS	15	35	16	42	—

Table B–42. Mississippi Site 6 Left, IRI Filter.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	81	45	70	56	71	77
02	50	74	43	36	63	54
03	73	39	86	60	72	77
05	60	34	61	46	57	60
06	74	58	71	55	**94**	79
DS	78	49	74	57	78	—

Table B–43. Mississippi Site 6 Left, Long Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	94	84	75	72	90	82
02	85	88	77	67	83	83
03	74	76	95	74	83	93
05	72	66	74	69	78	77
06	89	82	83	77	98	90
DS	81	82	93	77	90	—

Table B–44. Mississippi Site 6 Left, Medium Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	78	33	63	47	61	69
02	39	68	33	28	57	45
03	69	29	82	55	67	69
05	55	27	57	41	51	54
06	68	49	65	47	93	74
DS	76	39	65	49	72	—

Table B–45. Mississippi Site 6 Left, Short Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	54	6	13	8	11	15
02	11	45	8	8	15	13
03	28	13	59	23	20	22
05	22	12	23	16	15	16
06	28	15	16	10	71	30
DS	36	14	16	11	35	—

Table B–46. Mississippi Site 6 Right, IRI Filter.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	77	48	43	70	61
03	46	92	71	77	84
05	42	70	60	67	67
06	66	76	67	**98**	82
DS	60	84	69	86	—

Table B–47. Mississippi Site 6 Right, Long Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	91	82	70	89	90
03	82	97	78	82	91
05	69	77	77	75	75
06	90	82	75	99	91
DS	89	92	75	91	—

Table B–48. Mississippi Site 6 Right, Medium Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	69	37	35	62	52
03	36	91	68	70	80
05	35	67	56	63	63
06	56	68	59	97	77
DS	50	77	64	83	—

Table B–49. Mississippi Site 6 Right, Short Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	41	6	10	12	13
03	11	71	31	11	39
05	11	21	21	17	21
06	11	9	13	81	25
DS	11	22	14	26	—

Table B–50. Mississippi Site 7 Left, IRI Filter.

Correlation Reference	Correlated Device				
	01	02	05	06	DS
01	80	62	65	81	75
02	64	82	53	75	64
05	62	51	65	70	73
06	77	71	71	**98**	85
DS	71	60	73	84	—

Table B–51. Mississippi Site 7 Left, Long Wavelengths.

Correlation Reference	Correlated Device				
	01	02	05	06	DS
01	96	90	77	95	85
02	90	96	73	91	85
05	76	73	89	79	82
06	95	91	79	99	88
DS	85	84	82	88	—

Table B–52. Mississippi Site 7 Left, Medium Wavelengths.

Correlation Reference	Correlated Device				
	01	02	05	06	DS
01	74	48	59	76	72
02	52	72	44	68	54
05	56	40	54	64	66
06	71	61	65	97	83
DS	66	47	63	81	—

Table B–53. Mississippi Site 7 Left, Short Wavelengths.

Correlation Reference	Correlated Device				
	01	02	05	06	DS
01	37	6	7	16	21
02	11	31	9	14	9
05	22	9	14	18	21
06	28	11	9	70	40
DS	29	6	10	36	—

Table B–54. Mississippi Site 7 Right, IRI Filter.

Correlation Reference	Correlated Device			
	02	05	06	DS
02	79	49	71	65
05	47	59	70	68
06	67	71	**98**	90
DS	61	69	89	—

Table B–55. Mississippi Site 7 Right, Long Wavelengths.

Correlation Reference	Correlated Device			
	02	05	06	DS
02	96	70	89	85
05	70	79	77	76
06	89	77	99	90
DS	84	77	90	—

Table B–56. Mississippi Site 7 Right, Medium Wavelengths.

Correlation Reference	Correlated Device			
	02	05	06	DS
02	67	42	63	56
05	38	51	65	63
06	56	64	98	88
DS	49	62	89	—

Table B–57. Mississippi Site 7 Right, Short Wavelengths.

Correlation Reference	Correlated Device			
	02	05	06	DS
02	28	10	10	9
05	9	17	20	25
06	9	13	77	42
DS	7	13	36	—

Table B–58. Mississippi Site 8 Left, IRI Filter.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	57	33	60	47	57	57
02	35	55	39	34	52	46
03	56	36	87	60	76	74
05	46	31	63	50	62	61
06	53	47	77	58	93	78
DS	54	41	80	61	84	—

Table B–59. Mississippi Site 8 Left, Long Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	87	70	77	71	89	80
02	71	86	74	57	76	77
03	77	73	98	70	83	95
05	71	56	70	66	77	71
06	89	74	83	77	98	88
DS	80	76	95	71	87	—

Table B–60. Mississippi Site 8 Left, Medium Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	53	28	61	44	55	55
02	32	48	36	31	49	41
03	56	31	84	57	71	69
05	44	27	62	47	58	58
06	51	41	72	52	91	72
DS	53	35	78	57	81	—

Table B–61. Mississippi Site 8 Left, Short Wavelengths.

Correlation Reference	Correlated Device					
	01	02	03	05	06	DS
01	30	5	16	8	8	11
02	9	19	8	7	9	8
03	28	6	55	22	14	28
05	20	6	26	17	15	18
06	20	8	15	11	53	28
DS	24	7	38	18	35	—

Table B–62. Mississippi Site 8 Right, IRI Filter.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	57	43	42	55	52
03	40	93	62	80	75
05	40	67	57	66	66
06	51	80	61	**97**	74
DS	47	81	63	80	—

Table B–63. Mississippi Site 8 Right, Long Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	90	80	67	80	83
03	80	98	74	83	95
05	66	74	78	83	75
06	79	83	84	99	85
DS	82	95	75	87	—

Table B–64. Mississippi Site 8 Right, Medium Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	51	36	35	49	45
03	31	91	59	76	69
05	33	66	54	62	61
06	42	75	56	96	69
DS	38	79	58	78	—

Table B–65. Mississippi Site 8 Right, Short Wavelengths.

Correlation Reference	Correlated Device				
	02	03	05	06	DS
02	27	9	9	13	11
03	6	70	24	20	31
05	8	32	19	21	22
06	9	21	14	79	32
DS	7	37	17	44	—

Table B–66. Nevada Site 1 Left, IRI Filter.

Correlation	Correlated Device						
Reference	03	04	06	07	08	09	DS
03	68	42	70	61	60	60	60
04	47	51	47	42	38	35	35
06	63	42	78	77	67	66	66
07	55	39	73	92	66	57	57
08	55	36	66	68	**94**	75	75
09	54	32	62	58	74	91	93
DS	54	33	63	58	73	93	—

Table B–67. Nevada Site 1 Left, Long Wavelengths.

Correlation	Correlated Device						
Reference	03	04	06	07	08	09	DS
03	92	31	77	80	73	77	81
04	31	57	28	25	27	27	29
06	77	28	93	71	88	92	92
07	80	24	71	97	75	75	76
08	73	27	88	75	96	92	90
09	76	27	91	74	92	97	96
DS	80	29	92	75	90	96	—

Table B–68. Nevada Site 1 Left, Medium Wavelengths.

Correlation	Correlated Device						
Reference	03	04	06	07	08	09	DS
03	60	39	65	55	56	55	55
04	48	48	46	43	38	34	34
06	54	38	76	76	64	61	62
07	47	37	71	90	62	52	52
08	49	33	64	65	93	71	69
09	46	29	58	54	69	88	91
DS	46	30	59	53	67	91	—

Table B–69. Nevada Site 1 Left, Short Wavelengths.

Correlation	Correlated Device						
Reference	03	04	06	07	08	09	DS
03	29	14	22	20	23	18	16
04	20	27	16	20	13	13	13
06	14	11	47	22	21	12	19
07	16	16	35	64	27	17	23
08	17	11	31	23	77	20	26
09	12	9	27	21	25	56	55
DS	12	9	28	19	25	55	—

Table B–70. Nevada Site 1 Right, IRI Filter.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	77	50	77	74	76	71	74
04	55	56	52	50	47	43	44
06	71	47	81	82	82	77	79
07	69	46	77	93	82	74	76
08	71	44	80	83	92	85	88
09	65	40	72	74	84	90	93
DS	68	41	76	76	87	93	—

Table B–71. Nevada Site 1 Right, Long Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	95	34	85	83	81	83	84
04	34	70	29	29	29	30	30
06	84	29	95	73	87	91	92
07	82	28	72	98	85	81	82
08	81	29	87	85	97	95	96
09	83	30	91	81	95	97	98
DS	83	30	91	82	96	98	—

Table B–72. Nevada Site 1 Right, Medium Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	70	46	72	70	73	66	69
04	55	52	51	52	47	42	43
06	62	44	75	81	78	72	74
07	62	46	77	92	80	70	73
08	65	41	76	81	89	81	84
09	57	36	67	70	80	87	91
DS	60	37	70	71	82	91	—

Table B–73. Nevada Site 1 Right, Short Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	36	17	29	27	36	24	23
04	22	30	19	25	18	13	12
06	19	14	41	26	32	18	27
07	21	20	39	68	40	23	25
08	27	15	40	31	70	33	45
09	18	10	31	22	42	69	62
DS	19	10	33	20	39	61	—

Table B–74. Nevada Site 2 Left, IRI Filter.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	37	23	33	35	38	32	31
04	26	21	20	21	23	19	19
06	30	18	48	50	55	48	47
07	33	19	47	91	67	64	64
08	35	21	51	69	89	62	61
09	30	17	44	64	61	80	83
DS	29	18	44	64	60	83	—

Table B–75. Nevada Site 2 Left, Long Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	81	53	55	77	63	64	65
04	54	69	36	51	37	39	41
06	57	37	84	57	83	85	81
07	76	51	53	98	60	62	63
08	65	39	83	64	96	94	92
09	65	41	85	66	93	95	94
DS	68	44	82	69	92	95	—

Table B–76. Nevada Site 2 Left, Medium Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	25	15	25	24	29	23	21
04	18	14	14	14	17	13	13
06	21	12	36	41	44	35	34
07	21	12	37	87	56	44	47
08	25	14	40	58	84	48	47
09	19	11	31	47	47	63	69
DS	18	11	31	50	45	69	—

Table B–77. Nevada Site 2 Left, Short Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	11	6	9	8	12	7	8
04	11	9	5	5	7	6	5
06	5	3	18	16	13	3	4
07	6	4	18	52	15	4	6
08	8	5	17	17	53	4	7
09	6	4	8	5	6	19	19
DS	6	4	9	9	10	19	—

Table B–78. Nevada Site 2 Right, IRI Filter.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	49	32	41	39	42	38	37
04	36	30	30	29	29	23	23
06	39	27	45	50	53	42	41
07	36	26	47	93	79	61	60
08	39	26	49	80	91	79	77
09	35	21	39	61	77	**95**	**95**
DS	34	21	38	59	75	**95**	—

Table B–79. Nevada Site 2 Right, Long Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	84	64	61	76	65	65	62
04	64	77	46	56	46	47	45
06	61	46	85	59	86	85	86
07	75	56	59	97	66	64	64
08	65	46	86	67	98	96	96
09	65	47	85	65	96	96	96
DS	63	45	86	65	96	97	—

Table B–80. Nevada Site 2 Right, Medium Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	40	23	34	30	37	30	28
04	28	24	25	23	24	17	16
06	31	21	38	45	47	33	32
07	26	19	40	90	72	50	49
08	32	21	42	74	86	68	66
09	26	15	29	49	66	92	92
DS	25	14	28	46	63	92	—

Table B–81. Nevada Site 2 Right, Short Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	20	8	13	10	16	10	8
04	12	12	10	9	9	5	4
06	8	6	16	18	17	9	10
07	6	7	17	65	24	17	17
08	11	7	16	23	51	14	14
09	6	3	8	18	14	75	60
DS	5	3	7	14	11	60	—

Table B–82. Nevada Site 3 Left, IRI Filter.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	66	54	33	53	51	62	64
04	60	65	31	42	40	59	61
06	35	30	36	24	22	35	37
07	48	38	23	77	72	37	37
08	46	36	20	72	81	40	40
09	64	56	34	39	41	85	90
DS	67	57	36	38	41	89	—

Table B–83. Nevada Site 3 Left, Long Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	86	30	70	70	61	77	79
04	31	41	27	21	17	27	27
06	70	27	76	47	59	80	82
07	70	21	47	90	64	55	55
08	60	17	59	64	93	71	71
09	77	26	80	55	72	92	95
DS	79	27	81	55	71	95	—

Table B–84. Nevada Site 3 Left, Medium Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	61	54	32	50	49	58	61
04	62	64	35	44	42	58	61
06	34	32	37	24	22	34	37
07	43	37	22	75	70	33	33
08	42	36	20	70	80	37	37
09	59	53	35	35	39	84	89
DS	62	55	37	35	39	89	—

Table B–85. Nevada Site 3 Left, Short Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	36	25	20	27	36	21	22
04	32	37	18	25	28	17	16
06	13	12	25	21	26	10	12
07	19	18	19	75	49	11	13
08	24	20	20	45	78	15	17
09	19	15	16	13	18	73	71
DS	19	15	16	15	20	71	—

Table B–86. Nevada Site 3 Right, IRI Filter.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	55	33	36	49	41	50	46
04	37	40	22	31	25	29	26
06	33	20	34	38	34	37	35
07	45	28	36	90	67	50	49
08	38	23	31	65	91	63	66
09	46	26	35	52	64	**94**	92
DS	43	24	33	51	68	92	—

Table B–87. Nevada Site 3 Right, Long Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	90	25	71	78	68	74	69
04	26	74	20	20	14	16	14
06	69	15	75	61	76	80	79
07	78	19	62	96	71	71	69
08	67	14	75	71	98	92	95
09	73	16	80	71	92	97	96
DS	69	14	78	70	95	96	—

Table B–88. Nevada Site 3 Right, Medium Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	39	25	21	39	31	38	33
04	31	28	16	28	22	23	21
06	17	12	23	26	23	23	22
07	32	23	23	86	59	41	39
08	26	18	21	57	88	51	56
09	31	19	21	43	54	93	90
DS	28	17	20	41	58	90	—

Table B–89. Nevada Site 3 Right, Short Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	20	10	11	16	16	13	9
04	14	16	9	14	11	9	7
06	6	5	17	15	19	8	9
07	10	9	18	76	21	22	20
08	10	7	16	17	76	12	18
09	8	6	10	25	15	84	69
DS	6	5	8	16	19	69	—

Table B–90. Nevada Site 4 Left, IRI Filter.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	60	64	49	54	69	60	58
04	59	80	63	69	72	66	68
06	50	66	60	64	59	59	65
07	50	64	55	87	58	46	50
08	67	74	55	60	86	72	67
09	57	67	56	47	71	84	85
DS	54	65	59	51	65	85	—

Table B–91. Nevada Site 4 Left, Long Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	90	81	70	73	80	80	80
04	81	84	67	67	77	78	78
06	81	78	79	73	87	90	90
07	73	67	62	95	81	78	78
08	80	77	75	82	98	94	93
09	79	77	78	79	94	96	97
DS	79	77	78	79	93	97	—

Table B–92. Nevada Site 4 Left, Medium Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	47	56	37	46	62	50	49
04	49	73	54	66	66	57	61
06	37	54	48	62	49	45	53
07	40	58	50	83	54	38	44
08	59	69	44	56	85	66	59
09	46	58	42	39	64	76	77
DS	43	55	47	45	58	77	—

Table B–93. Nevada Site 4 Left, Short Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	20	23	12	11	32	11	14
04	16	39	25	23	35	10	13
06	9	17	31	13	20	5	8
07	10	23	19	52	21	8	11
08	24	32	24	18	66	13	23
09	12	15	11	10	18	34	32
DS	11	13	12	9	21	32	—

Table B–94. Nevada Site 4 Right, IRI Filter.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	59	66	54	54	65	62	62
04	61	77	64	69	75	66	68
06	56	69	62	66	70	62	66
07	50	64	56	88	61	50	56
08	61	74	62	63	84	77	80
09	58	65	55	51	77	84	87
DS	58	64	56	58	79	87	—

Table B–95. Nevada Site 4 Right, Long Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	90	83	73	75	79	82	82
04	82	87	70	72	79	81	81
06	84	81	78	74	87	89	88
07	74	72	63	94	85	82	83
08	79	79	74	85	98	95	96
09	81	81	76	82	96	98	98
DS	81	80	75	83	96	98	—

Table B–96. Nevada Site 4 Right, Medium Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	46	56	43	46	58	51	53
04	51	71	56	66	69	56	62
06	43	58	51	65	60	49	58
07	40	58	52	84	56	41	51
08	53	68	53	58	81	70	75
09	47	55	44	43	70	74	79
DS	47	55	48	53	72	80	—

Table B–97. Nevada Site 4 Right, Short Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	22	20	13	11	25	11	12
04	15	38	23	22	28	10	12
06	9	16	30	12	18	5	12
07	10	21	18	48	14	9	7
08	17	23	24	11	55	15	25
09	11	12	11	9	18	38	36
DS	9	11	15	5	20	36	—

Table B–98. Nevada Site 5 Left, IRI Filter.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	45	49	45	41	52	47	47
04	47	56	53	48	57	51	50
06	43	51	61	60	71	48	47
07	38	44	53	81	64	35	36
08	48	53	63	66	93	64	64
09	45	48	47	37	65	89	91
DS	45	48	46	36	65	91	—

Table B–99. Nevada Site 5 Left, Long Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	86	74	72	72	79	77	76
04	75	80	61	58	64	65	64
06	80	69	80	69	88	88	87
07	72	58	60	95	79	72	74
08	78	64	77	79	98	94	95
09	76	64	77	72	94	97	97
DS	75	63	76	74	95	97	—

Table B–100. Nevada Site 5 Left, Medium Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	30	37	32	31	42	37	36
04	33	43	41	42	49	43	42
06	28	38	50	58	65	37	37
07	25	35	48	75	59	29	30
08	35	42	56	61	92	57	58
09	32	38	36	30	59	85	88
DS	32	37	35	31	59	88	—

Table B–101. Nevada Site 5 Left, Short Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	12	10	6	6	11	8	8
04	7	13	10	11	8	7	7
06	4	6	22	13	16	4	7
07	4	8	20	34	12	5	8
08	8	7	21	9	63	11	22
09	5	5	10	8	16	27	30
DS	6	4	11	8	27	30	—

Table B–102. Nevada Site 5 Right, IRI Filter.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	53	56	51	48	44	50	51
04	53	64	59	56	47	52	54
06	49	58	69	68	59	57	57
07	44	52	60	83	63	46	45
08	41	44	52	62	93	61	59
09	46	49	55	48	63	91	93
DS	48	50	54	47	60	93	—

Table B–103. Nevada Site 5 Right, Long Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	90	77	74	75	63	72	75
04	77	82	62	60	53	61	64
06	84	72	82	71	69	81	84
07	75	60	62	93	71	78	80
08	63	52	60	72	97	84	81
09	72	61	71	78	85	94	96
DS	74	63	73	80	82	96	—

Table B–104. Nevada Site 5 Right, Medium Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	36	40	35	36	36	40	40
04	36	50	46	49	41	43	44
06	32	43	57	67	56	42	42
07	29	41	55	77	56	35	34
08	30	34	45	55	90	53	51
09	33	38	39	36	55	89	91
DS	34	39	38	35	53	91	—

Table B–105. Nevada Site 5 Right, Short Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	16	13	10	11	12	12	12
04	10	21	14	19	11	10	11
06	6	10	33	15	16	5	9
07	8	13	24	39	13	11	17
08	9	8	21	10	61	11	15
09	7	8	12	13	16	39	40
DS	6	9	13	12	19	41	—

Table B–106. Nevada Site 6 Left, IRI Filter.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	28	33	31	32	39	33	37
04	31	48	40	37	45	43	48
06	27	35	41	47	55	47	51
07	28	33	43	82	73	49	52
08	34	41	51	75	87	66	70
09	29	38	43	51	68	80	79
DS	34	44	48	54	72	79	—

Table B–107. Nevada Site 6 Left, Long Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	57	13	55	54	58	56	57
04	13	41	15	9	13	13	15
06	54	15	62	52	70	67	70
07	53	9	51	91	76	67	62
08	58	13	69	76	94	83	86
09	55	13	66	68	84	84	86
DS	57	15	70	63	86	86	—

Table B–108. Nevada Site 6 Left, Medium Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	24	31	28	29	37	31	34
04	27	42	41	40	50	46	50
06	23	33	40	49	55	44	48
07	24	33	44	80	68	42	48
08	31	41	51	71	83	60	67
09	26	37	42	44	62	76	78
DS	30	42	47	50	70	78	—

Table B–109. Nevada Site 6 Left, Short Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	15	12	12	12	19	10	14
04	10	14	16	16	21	8	14
06	6	9	31	20	21	5	13
07	8	11	29	52	31	4	10
08	13	15	30	38	44	10	26
09	9	10	16	7	15	22	22
DS	10	11	22	12	24	22	—

Table B–110. Nevada Site 6 Right, IRI Filter.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	43	48	45	48	42	46	48
04	44	63	56	61	53	56	60
06	39	50	56	65	56	55	59
07	42	54	60	86	72	59	62
08	37	47	51	70	87	70	68
09	40	49	51	61	73	89	90
DS	42	54	55	64	70	90	—

Table B–111. Nevada Site 6 Right, Long Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	61	21	53	58	49	52	52
04	22	44	24	18	22	23	23
06	52	24	65	53	62	68	67
07	57	18	53	90	68	66	72
08	48	21	62	68	95	86	87
09	51	23	67	66	86	91	90
DS	52	23	67	72	87	90	—

Table B–112. Nevada Site 6 Right, Medium Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	39	45	42	46	41	44	46
04	39	58	56	63	55	57	60
06	34	46	55	65	56	52	56
07	37	52	60	85	69	55	58
08	34	45	52	69	84	67	66
09	35	47	50	57	71	86	88
DS	37	51	53	60	69	88	—

Table B–113. Nevada Site 6 Right, Short Wavelengths.

Correlation Reference	Correlated Device						
	03	04	06	07	08	09	DS
03	24	22	20	25	24	16	24
04	18	27	27	32	27	14	25
06	12	16	46	26	21	8	19
07	17	23	38	64	31	10	21
08	17	21	31	33	47	17	30
09	15	17	24	14	24	29	34
DS	16	19	29	18	26	34	—

Table B–114. Pennsylvania Site 1 Left, IRI Filter.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	**96**	80	80	90	80	85	91	89	88	90	88	88	86
02	82	90	77	76	86	79	86	79	84	82	86	80	77
03	85	82	89	85	78	82	85	80	85	84	82	86	76
04	91	80	86	**96**	77	87	86	86	85	90	82	89	80
05	80	82	72	75	92	76	84	77	81	76	81	77	73
06	91	86	84	88	82	90	89	87	90	90	86	89	80
07	91	80	77	84	84	82	93	85	87	84	87	85	85
08	90	79	76	86	79	84	88	88	87	84	85	84	80
73	89	83	80	83	83	84	91	85	92	85	90	85	84
74	92	84	80	86	81	84	91	86	89	92	90	89	87
75	87	80	76	79	81	80	87	82	86	82	90	81	88
76	91	82	82	86	81	83	90	84	88	89	88	91	84
DS	84	70	69	77	72	72	83	77	76	78	80	77	—

Table B–115. Pennsylvania Site 1 Left, Long Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	96	67	73	87	78	77	84	81	81	84	83	84	89
02	68	89	84	63	83	86	77	72	86	83	83	82	63
03	73	84	89	69	82	82	80	78	83	83	82	83	69
04	87	62	69	82	70	71	75	76	74	76	76	77	82
05	78	83	82	70	99	88	92	74	92	94	92	94	72
06	77	86	82	71	89	94	84	75	95	92	92	91	71
07	84	77	80	75	92	83	96	78	86	89	88	89	78
08	82	72	78	76	74	74	78	81	77	79	79	80	73
73	81	86	83	74	92	94	87	78	97	96	96	95	74
74	84	82	83	77	94	91	90	80	95	97	95	97	76
75	83	83	82	76	92	92	88	79	95	96	95	95	75
76	85	81	83	78	93	90	90	80	94	97	95	97	77
DS	89	63	68	82	72	70	78	73	74	76	75	77	—

Table B–116. Pennsylvania Site 1 Left, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	95	75	77	88	75	85	90	86	86	88	83	86	84
02	73	85	67	69	81	70	77	70	76	74	77	71	75
03	80	74	84	80	72	75	81	71	79	78	77	79	76
04	89	74	84	96	72	86	85	83	80	86	77	85	77
05	74	76	64	69	89	69	77	70	73	67	74	68	68
06	89	79	77	82	77	86	88	81	87	85	83	83	81
07	89	76	73	82	77	80	88	81	85	80	82	81	82
08	87	73	72	83	72	82	83	85	82	80	79	79	75
73	82	77	73	77	77	79	84	76	88	79	84	78	82
74	85	78	74	80	76	78	86	77	83	89	84	83	88
75	80	74	69	73	76	74	81	73	80	75	84	73	82
76	85	75	76	81	75	77	85	75	82	83	81	86	83
DS	80	68	65	73	69	69	80	71	72	75	78	73	—

Table B–117. Pennsylvania Site 1 Left, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	88	52	44	61	55	60	64	68	70	70	60	66	68
02	39	66	42	38	52	41	41	37	51	51	52	51	38
03	34	43	65	39	40	41	35	29	52	50	52	51	31
04	72	61	60	79	61	63	65	57	70	75	65	73	58
05	50	49	43	42	81	47	54	47	52	50	53	46	37
06	51	44	45	43	48	64	45	46	65	61	61	58	40
07	64	48	43	51	54	56	60	56	62	58	58	60	47
08	73	49	40	50	55	61	57	74	65	59	63	58	53
73	45	45	45	39	44	52	42	42	75	55	58	54	37
74	48	45	43	40	43	49	43	43	55	75	55	58	44
75	49	45	44	37	47	49	42	43	57	54	69	50	48
76	45	47	45	42	44	48	42	38	56	60	52	68	42
DS	50	39	34	34	40	38	41	41	45	54	56	49	—

Table B–118. Pennsylvania Site 1 Right, IRI Filter

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	**94**	81	77	86	86	83	87	92	90	89	89	86	89
02	86	88	76	76	80	78	80	85	85	83	85	81	78
03	84	81	89	87	88	83	88	80	86	86	83	87	78
04	87	78	85	**95**	90	84	92	83	86	85	81	89	80
05	87	82	86	91	**95**	87	**94**	82	90	88	85	92	81
06	89	84	85	87	89	89	90	85	90	89	86	90	80
07	89	81	84	92	**94**	86	**96**	84	90	89	86	91	83
08	92	80	74	81	81	79	83	92	86	83	86	82	86
73	92	84	81	83	85	84	86	89	92	88	90	86	85
74	91	82	79	83	85	82	85	88	87	91	89	88	88
75	89	80	76	78	80	78	81	86	85	84	90	80	89
76	90	81	82	87	87	83	88	87	89	90	88	92	86
DS	85	71	71	78	78	73	79	83	78	79	83	78	—

Table B–119. Pennsylvania Site 1 Right, Long Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	98	84	78	88	87	79	85	95	84	84	87	83	90
02	84	94	89	77	89	88	89	83	93	92	94	91	77
03	78	90	92	72	84	89	85	77	91	90	89	91	72
04	88	77	72	82	80	72	78	85	77	77	79	76	84
05	87	89	84	80	99	85	98	83	89	89	91	88	80
06	80	89	90	73	85	96	85	77	94	94	91	95	73
07	84	89	84	78	98	85	98	81	90	89	91	88	78
08	95	82	77	85	83	76	81	93	82	81	84	80	87
73	85	93	91	77	89	94	90	82	98	97	96	97	77
74	85	92	90	77	89	94	89	82	97	97	96	97	77
75	87	94	88	79	91	90	91	85	96	95	97	94	79
76	84	92	91	76	88	94	89	81	97	97	95	97	76
DS	89	77	72	84	80	72	78	86	77	77	79	76	—

Table B–120. Pennsylvania Site 1 Right, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	94	76	73	82	83	83	86	90	87	86	83	83	87
02	79	83	66	67	70	71	72	77	77	76	79	72	76
03	79	73	85	81	81	78	82	76	81	81	78	81	78
04	83	71	84	95	90	83	92	80	81	78	74	84	77
05	85	75	83	89	92	86	91	80	86	83	79	88	80
06	89	78	77	81	82	84	85	85	86	85	83	84	83
07	89	76	80	89	91	85	94	84	88	85	81	90	83
08	91	76	70	77	78	79	82	90	85	81	82	81	82
73	86	76	73	75	77	79	80	82	88	81	84	79	85
74	85	75	72	76	77	77	80	81	80	87	83	81	87
75	81	72	68	70	71	72	74	78	78	76	85	72	85
76	84	74	74	80	80	78	82	80	82	84	82	88	88
DS	82	67	67	73	75	71	78	78	75	77	83	76	—

Table B–121. Pennsylvania Site 1 Right, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	85	52	38	51	58	60	70	76	74	67	62	62	74
02	38	64	32	30	37	39	42	41	45	49	52	45	41
03	26	35	66	35	41	42	41	28	50	49	52	46	38
04	60	43	61	80	69	64	77	55	69	60	60	70	51
05	60	46	56	56	79	61	73	54	69	62	65	68	61
06	48	43	45	40	46	62	52	51	63	60	64	57	50
07	66	47	48	55	73	59	81	67	68	62	64	67	65
08	69	46	33	38	45	52	58	81	63	56	63	55	59
73	47	43	44	37	45	54	50	49	74	54	62	55	48
74	46	44	39	34	43	47	48	51	50	70	53	53	45
75	43	42	38	30	37	45	42	46	52	48	67	45	54
76	40	43	40	39	46	47	50	42	54	56	53	68	51
DS	47	39	35	31	43	41	48	49	47	51	62	50	—

Table B–122. Pennsylvania Site 2 Left, IRI Filter.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	92	52	44	71	55	50	78	70	62	78	70	79	60
02	57	59	45	56	50	47	59	59	58	62	58	55	49
03	47	48	49	50	34	47	49	46	52	51	50	49	47
04	72	52	46	71	43	48	68	65	61	69	65	65	59
05	56	45	31	42	87	31	59	43	43	55	47	51	34
06	53	49	45	51	34	49	52	53	55	54	55	53	50
07	79	54	45	67	59	48	82	64	60	76	68	76	56
08	71	55	43	66	44	49	65	73	61	69	67	65	59
73	66	54	46	64	46	49	66	64	61	68	66	65	58
74	82	55	46	68	60	48	78	66	61	79	69	77	56
75	76	52	44	66	50	49	72	65	61	74	69	74	57
76	83	48	44	65	54	47	73	62	59	72	67	81	56
DS	63	45	42	61	35	46	60	62	58	62	62	62	—

Table B–123. Pennsylvania Site 2 Left, Long Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	98	85	84	60	77	84	81	92	87	90	90	91	89
02	85	92	90	59	84	89	82	91	92	93	92	91	77
03	84	90	89	57	82	88	82	89	90	92	91	91	77
04	60	59	57	50	46	57	46	63	59	59	58	58	53
05	76	84	82	46	99	81	93	78	83	86	85	86	71
06	84	89	88	57	82	87	82	88	90	92	91	91	77
07	81	81	81	46	93	81	98	76	82	86	85	86	76
08	92	90	89	63	78	88	77	97	91	94	93	94	81
73	87	91	90	59	83	90	83	92	92	94	93	94	78
74	90	93	92	59	87	91	86	94	94	97	96	97	81
75	90	91	91	58	85	90	86	93	93	96	94	96	82
76	91	91	91	58	86	91	86	94	93	97	95	97	82
DS	89	77	77	53	71	77	76	81	78	81	81	82	—

Table B–124. Pennsylvania Site 2 Left, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	88	40	30	71	46	39	67	59	51	69	60	70	49
02	47	48	29	47	41	31	50	48	45	49	45	40	37
03	34	34	35	39	22	32	39	33	38	37	35	34	35
04	72	41	34	74	42	37	68	56	52	67	59	62	49
05	45	34	18	39	81	19	43	32	30	43	32	35	23
06	42	35	30	42	22	36	43	42	41	41	42	40	40
07	69	43	33	69	43	37	69	56	50	66	58	66	47
08	61	43	28	56	34	36	57	62	48	55	54	51	47
73	57	40	31	58	36	35	57	51	48	57	52	52	45
74	76	41	30	65	50	34	63	52	47	68	55	64	43
75	68	37	29	63	38	35	60	52	47	61	56	62	43
76	76	33	28	62	38	33	58	48	44	58	53	70	43
DS	53	33	29	54	25	34	52	51	46	50	49	50	—

Table B–125. Pennsylvania Site 2 Left, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	58	19	10	20	20	18	12	25	30	40	34	38	23
02	23	26	11	12	23	12	10	17	23	31	25	25	14
03	11	16	15	13	11	11	9	11	19	20	16	17	13
04	30	18	13	26	22	14	13	17	29	42	32	38	23
05	25	18	8	12	50	9	10	13	19	29	19	22	10
06	23	17	10	15	13	17	10	18	23	25	25	25	17
07	16	21	13	18	10	15	18	15	26	33	29	33	17
08	29	22	9	14	16	15	10	27	24	29	29	27	18
73	31	17	11	15	18	13	10	15	26	33	28	32	15
74	30	18	10	14	19	12	9	14	22	40	25	31	15
75	34	16	9	13	15	12	9	16	23	32	30	31	16
76	33	14	9	14	14	12	9	14	21	31	25	43	17
DS	31	14	10	15	14	13	10	17	22	31	27	34	—

Table B–126. Pennsylvania Site 2 Right, IRI Filter.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	88	59	43	66	75	52	72	85	63	76	73	77	75
02	63	67	48	46	51	54	49	57	62	65	59	54	48
03	46	51	45	39	41	46	39	43	50	51	46	45	39
04	66	43	37	60	61	42	60	66	51	58	58	65	62
05	75	47	38	59	86	45	81	73	55	65	64	76	74
06	55	53	42	45	49	49	47	53	57	57	55	53	47
07	72	45	36	60	81	43	83	71	52	62	61	73	69
08	86	53	39	67	74	49	71	88	59	70	69	78	76
73	67	57	45	54	59	53	56	63	62	69	65	63	56
74	80	59	45	61	71	52	68	75	64	75	71	74	67
75	76	53	41	61	69	50	66	74	61	71	70	73	66
76	78	49	40	67	79	48	77	78	57	68	67	81	76
DS	74	43	36	63	71	43	71	74	51	61	61	71	—

Table B–127. Pennsylvania Site 2 Right, Long Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	98	88	89	69	80	89	79	97	90	94	93	96	88
02	88	96	92	65	79	92	78	90	94	93	92	90	79
03	89	92	91	64	79	92	79	91	93	94	93	92	80
04	69	65	64	52	54	64	54	69	65	66	66	66	63
05	80	79	79	55	98	81	98	80	80	83	84	86	81
06	90	92	92	64	81	92	81	91	93	94	93	92	80
07	80	79	79	55	98	81	97	79	80	83	83	86	81
08	97	90	91	69	79	91	79	99	92	96	95	96	87
73	90	94	93	65	80	93	80	92	94	95	94	93	81
74	94	93	93	66	84	94	83	96	95	98	97	97	84
75	93	92	93	66	84	93	83	95	94	97	95	96	84
76	96	90	91	66	86	92	86	96	92	96	96	98	86
DS	88	79	80	63	82	80	81	87	80	84	84	86	—

Table B–128. Pennsylvania Site 2 Right, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	82	43	24	61	64	32	68	75	45	63	56	59	64
02	49	52	26	32	39	33	36	43	44	50	41	36	36
03	27	31	26	24	27	26	24	25	29	30	26	25	24
04	61	28	20	63	58	25	66	59	35	46	44	60	56
05	65	33	22	57	71	28	63	64	40	53	50	64	64
06	36	34	22	29	33	29	31	35	36	36	34	32	33
07	68	31	20	65	63	26	72	64	36	49	46	60	57
08	76	37	21	60	61	30	66	79	40	55	51	61	63
73	52	38	24	40	47	31	43	47	43	51	46	44	43
74	69	41	25	53	59	30	58	63	43	60	51	56	57
75	62	34	21	51	57	28	54	59	39	52	50	55	55
76	65	30	21	64	60	27	68	61	36	49	45	63	58
DS	66	30	20	62	60	27	63	65	36	50	47	59	—

Table B–129. Pennsylvania Site 2 Right, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	54	21	8	20	14	11	23	40	24	37	29	32	33
02	23	26	9	13	11	10	16	21	22	32	25	23	20
03	9	14	13	9	11	10	10	9	16	17	14	14	11
04	29	13	8	28	15	10	25	29	19	27	24	36	28
05	18	15	9	20	27	11	16	16	22	30	27	35	26
06	14	15	9	13	12	13	15	16	19	20	20	19	16
07	29	13	8	22	16	10	24	28	19	27	23	33	28
08	43	17	7	18	12	11	21	45	21	30	27	32	30
73	26	17	9	18	13	10	20	24	23	31	27	30	25
74	36	18	9	16	12	9	19	29	21	37	24	30	27
75	31	15	7	16	12	10	19	29	20	27	27	28	26
76	32	13	7	20	13	10	21	28	18	27	22	35	25
DS	36	14	7	18	13	10	21	32	18	27	23	29	—

Table B–130. Pennsylvania Site 3 Left, IRI Filter.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	91	43	41	85	80	30	84	89	40	48	45	45	82
02	45	48	45	46	44	33	46	46	44	51	48	49	44
03	43	44	46	46	40	33	42	42	44	48	48	49	44
04	86	44	44	87	75	30	80	83	42	49	46	47	78
05	81	41	37	73	**96**	26	90	81	35	43	39	40	75
06	31	35	35	32	29	25	31	31	34	37	37	37	32
07	85	42	39	79	90	28	91	85	38	46	41	43	80
08	90	42	39	82	81	29	85	92	38	47	43	43	85
73	42	47	47	43	38	33	41	42	47	51	49	51	41
74	51	48	46	51	47	34	50	51	45	52	50	51	49
75	47	46	46	48	42	33	45	47	45	51	49	51	47
76	48	47	48	49	43	34	46	47	46	52	51	51	48
DS	86	40	39	79	77	28	80	85	37	44	42	43	—

Table B–131. Pennsylvania Site 3 Left, Long Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	97	89	86	84	77	81	77	97	85	87	86	84	94
02	89	94	92	85	82	88	83	90	92	93	92	91	86
03	86	93	93	85	80	90	81	86	93	94	94	93	83
04	84	85	84	86	64	82	64	84	85	86	86	86	78
05	77	82	80	64	99	75	98	77	77	80	77	77	78
06	82	89	90	83	75	88	76	81	92	92	92	92	78
07	78	82	80	64	98	75	98	77	78	80	78	78	79
08	97	89	85	84	77	81	77	98	84	86	85	84	93
73	85	92	93	86	78	91	79	85	95	95	95	96	82
74	87	94	94	86	80	91	81	87	95	96	95	95	84
75	86	92	94	86	77	92	79	86	95	95	96	96	83
76	85	92	94	86	78	92	78	84	96	95	96	96	82
DS	94	85	82	78	77	78	78	93	81	83	82	81	—

Table B–132. Pennsylvania Site 3 Left, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	87	30	27	78	79	19	82	84	27	34	31	30	73
02	34	34	30	35	35	21	36	35	28	35	32	32	33
03	31	29	31	34	30	20	31	31	27	32	30	31	32
04	80	31	31	84	72	20	78	78	28	35	32	32	71
05	81	28	25	69	95	17	86	78	23	30	26	27	68
06	22	23	23	23	21	15	22	22	22	25	24	24	22
07	85	29	26	74	86	18	86	83	25	32	28	29	73
08	86	29	25	75	80	18	83	87	25	33	29	29	74
73	30	32	32	32	28	22	30	31	31	36	34	35	30
74	39	32	30	40	36	21	39	40	29	36	33	33	37
75	35	30	29	36	32	20	34	35	29	33	32	33	35
76	35	31	31	37	32	21	35	35	29	34	33	34	35
DS	79	26	25	71	73	18	76	76	23	29	27	28	—

Table B–133. Pennsylvania Site 3 Left, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	28	5	4	12	14	3	19	23	5	7	6	5	24
02	6	12	7	7	6	5	6	6	6	9	8	8	5
03	4	8	11	7	4	5	4	5	7	8	7	8	7
04	19	6	5	20	12	3	18	16	5	7	5	6	22
05	16	4	3	5	59	2	23	16	3	4	3	3	10
06	4	7	7	4	3	6	3	4	7	8	7	8	5
07	21	4	3	8	23	2	26	20	4	5	4	4	14
08	25	4	3	7	20	2	19	30	4	6	5	5	15
73	5	7	8	6	4	6	5	5	11	9	10	8	6
74	7	7	7	8	5	4	6	7	6	11	7	8	8
75	6	7	6	6	4	4	5	6	7	7	11	7	7
76	6	7	7	7	4	5	5	6	7	8	8	10	8
DS	19	4	4	9	12	3	18	18	4	5	5	5	—

Table B–134. Pennsylvania Site 3 Right, IRI Filter.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	88	45	55	71	79	46	84	85	48	54	50	44	67
02	47	53	46	36	42	49	48	45	53	52	48	47	37
03	57	41	58	51	59	46	60	55	48	54	51	46	50
04	71	34	49	84	82	39	72	75	40	45	44	39	77
05	80	39	55	83	**94**	44	86	83	45	52	48	43	78
06	47	46	51	41	48	48	50	46	51	55	52	49	42
07	85	45	57	73	86	47	92	82	49	56	51	45	69
08	87	42	51	75	83	43	82	91	45	52	47	41	74
73	50	49	53	41	48	51	53	49	53	58	52	50	41
74	56	47	57	46	55	50	60	55	53	59	54	49	47
75	52	43	55	46	52	48	54	50	49	55	52	48	46
76	46	43	52	40	47	49	49	45	50	54	52	48	41
DS	69	33	46	78	77	38	68	73	37	43	42	37	—

Table B–135. Pennsylvania Site 3 Right, Long Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	96	87	91	80	77	92	79	95	91	92	92	93	82
02	87	94	85	72	76	90	81	84	92	91	86	88	72
03	91	85	93	79	85	91	83	92	90	90	94	93	83
04	81	72	79	85	62	77	60	83	76	77	80	79	79
05	77	76	85	61	99	83	93	79	80	81	85	84	73
06	92	90	91	76	83	93	86	90	93	94	93	94	79
07	80	81	83	59	93	86	97	77	85	86	84	86	68
08	95	83	92	82	79	89	77	97	88	89	93	92	86
73	91	91	90	76	81	93	85	89	94	94	91	93	77
74	92	91	91	77	81	94	86	89	94	95	92	94	78
75	93	86	94	80	85	93	84	94	91	92	95	95	83
76	93	87	93	79	84	94	86	92	93	94	95	96	81
DS	82	72	83	79	72	78	68	86	77	77	83	80	—

Table B–136. Pennsylvania Site 3 Right, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	79	25	29	61	68	24	78	78	27	31	26	22	54
02	29	32	27	21	25	27	30	30	31	31	28	24	22
03	34	21	35	34	40	24	40	35	25	29	26	23	33
04	62	18	30	78	80	23	70	63	23	26	26	22	61
05	69	21	33	78	88	25	80	71	26	30	27	24	64
06	28	24	30	26	31	27	32	29	28	32	29	26	27
07	79	24	33	72	80	26	86	81	28	32	28	24	64
08	80	24	28	63	73	24	80	85	26	31	25	22	58
73	31	27	32	26	31	28	34	32	31	34	30	26	26
74	35	24	33	30	37	27	40	38	28	35	28	25	30
75	30	22	32	30	34	26	34	31	27	31	30	26	30
76	26	22	31	26	29	27	30	27	27	31	30	27	25
DS	57	17	26	65	69	21	63	59	20	24	23	20	—

Table B–137. Pennsylvania Site 3 Right, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	39	6	6	13	20	5	30	35	8	9	7	6	13
02	9	13	10	5	6	7	9	8	9	9	8	7	6
03	9	6	14	8	11	5	9	8	7	7	7	6	9
04	16	4	6	28	34	5	29	17	6	6	6	6	12
05	20	4	7	17	53	4	43	23	7	5	5	5	15
06	8	7	9	8	9	10	9	8	8	10	9	8	7
07	31	5	6	15	43	5	51	38	7	7	6	5	14
08	36	6	5	11	27	5	42	50	7	9	6	5	9
73	10	7	10	8	10	7	11	10	13	8	10	8	9
74	12	6	8	8	10	7	13	12	7	16	8	8	9
75	9	6	9	8	9	6	10	9	9	9	11	8	8
76	7	6	9	8	8	7	8	6	9	10	9	11	7
DS	12	3	4	10	22	3	21	12	5	4	4	4	—

Table B–138. Pennsylvania Site 4 Left, IRI Filter.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	**96**	55	53	88	81	57	81	93	52	58	56	58	86
02	56	61	60	52	55	57	54	58	58	64	62	63	53
03	54	61	63	52	52	57	52	55	61	65	64	67	51
04	88	51	50	86	78	53	78	86	50	54	52	55	85
05	81	52	50	78	**97**	54	**94**	78	49	54	50	54	83
06	58	56	56	54	56	52	56	59	53	58	56	58	54
07	82	52	49	78	**94**	54	93	78	49	54	50	54	84
08	93	55	52	86	79	57	79	93	52	58	56	58	84
73	54	58	59	51	51	54	51	55	55	62	60	63	51
74	59	64	63	56	56	58	56	61	61	67	64	67	56
75	57	62	63	53	52	57	52	59	60	66	63	67	53
76	60	62	64	56	56	59	56	61	62	67	65	69	56
DS	87	50	48	86	82	52	83	84	47	53	50	53	—

Table B–139. Pennsylvania Site 4 Left, Long Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	98	81	81	88	87	80	87	96	82	83	83	83	89
02	81	92	91	75	82	90	81	83	92	92	92	92	73
03	80	91	91	74	80	90	80	82	92	92	92	92	72
04	88	75	75	84	79	74	79	87	76	76	76	77	87
05	87	82	80	79	98	80	97	87	82	83	82	82	79
06	79	90	90	73	80	89	79	81	91	91	90	91	71
07	88	81	80	79	97	79	97	87	81	82	81	82	80
08	96	84	82	87	87	82	86	96	84	85	84	84	86
73	82	92	92	76	82	90	81	83	93	94	93	94	73
74	82	92	92	76	83	90	82	84	94	94	94	94	74
75	82	92	92	76	82	90	81	84	93	94	93	94	74
76	82	92	92	76	82	91	82	84	94	94	94	95	74
DS	88	73	72	87	79	71	81	86	73	74	74	74	—

Table B–140. Pennsylvania Site 4 Left, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	85	17	16	73	57	28	59	78	17	21	18	21	74
02	20	22	19	20	18	21	18	21	19	23	20	20	20
03	19	20	25	21	16	21	16	19	22	24	22	25	20
04	75	17	18	77	54	28	56	73	18	21	18	22	69
05	59	15	13	51	91	22	73	56	12	15	13	15	55
06	31	17	17	32	26	23	26	31	17	20	17	20	31
07	61	15	13	53	73	22	69	59	13	16	13	15	58
08	80	17	15	70	57	27	60	80	16	20	17	19	72
73	19	20	21	21	15	20	16	20	20	23	21	23	19
74	24	22	21	24	19	24	20	25	21	29	22	25	26
75	21	22	23	21	16	21	17	22	22	26	25	26	20
76	24	19	22	25	18	24	19	24	22	25	23	28	24
DS	80	15	16	68	59	26	61	73	15	20	15	19	—

Table B–141. Pennsylvania Site 4 Left, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	36	4	3	14	10	5	11	27	4	5	4	5	36
02	4	11	7	5	4	8	5	5	8	8	7	8	5
03	4	7	12	5	3	8	5	5	7	8	7	8	5
04	22	4	4	19	11	6	10	24	4	5	4	5	32
05	10	2	2	5	46	3	12	11	2	3	3	2	10
06	7	6	5	8	5	9	6	7	5	5	6	6	7
07	14	3	3	7	12	4	14	15	3	4	3	3	13
08	29	3	3	12	14	5	11	32	3	5	4	4	24
73	4	8	8	5	3	8	4	5	10	8	8	8	4
74	6	7	7	6	4	8	5	6	6	12	7	9	6
75	5	8	8	5	4	8	5	6	8	9	13	9	5
76	5	7	7	6	3	8	5	5	7	9	7	13	5
DS	26	3	3	11	14	4	8	23	2	4	3	3	—

Table B–142. Pennsylvania Site 4 Right, IRI Filter.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	**97**	65	56	73	89	72	85	91	62	60	74	77	88
02	66	73	65	49	63	76	68	61	68	69	73	74	62
03	57	67	62	43	56	70	58	54	63	64	67	67	55
04	73	48	42	83	72	53	64	78	47	45	56	59	77
05	89	61	54	73	**96**	69	88	85	59	56	70	74	87
06	73	74	67	54	71	79	75	67	71	69	79	81	68
07	85	65	56	64	88	73	**94**	77	62	60	73	77	78
08	91	59	52	78	83	66	74	**95**	57	55	69	72	92
73	63	67	60	48	62	72	64	59	62	63	71	73	60
74	61	70	62	45	59	72	63	58	65	66	70	70	58
75	75	70	62	57	72	78	75	71	69	66	79	82	71
76	78	70	62	60	76	79	79	73	69	65	80	83	74
DS	89	59	52	78	86	66	77	92	57	54	68	72	—

Table B–143. Pennsylvania Site 4 Right, Long Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	99	75	73	77	86	73	83	94	76	78	77	77	92
02	75	95	92	61	79	93	81	72	94	93	94	94	70
03	74	92	91	60	79	92	80	71	92	92	92	92	69
04	78	61	60	78	70	60	67	81	63	65	64	65	80
05	85	79	78	69	99	78	96	82	80	83	82	83	80
06	73	93	92	59	79	93	80	70	92	92	93	93	69
07	83	80	79	67	96	79	98	79	81	84	82	83	77
08	95	72	71	80	83	70	79	95	73	76	75	75	93
73	76	94	91	63	81	92	82	73	94	94	95	95	71
74	78	93	91	64	83	92	84	75	94	96	96	96	72
75	77	94	92	64	82	93	83	75	95	96	97	97	72
76	77	93	92	64	83	93	84	75	95	96	97	97	72
DS	92	69	69	80	81	68	77	92	71	73	72	73	—

Table B–144. Pennsylvania Site 4 Right, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	91	38	22	64	79	52	81	81	30	26	44	49	76
02	42	41	26	30	38	44	45	39	34	31	40	41	37
03	25	31	25	20	26	31	27	24	27	27	29	29	25
04	64	26	17	73	72	40	58	69	24	19	35	41	63
05	80	33	21	73	86	48	74	79	29	24	40	47	75
06	57	38	24	44	55	49	60	53	32	27	44	49	53
07	82	39	22	60	74	53	84	72	31	27	43	49	70
08	81	33	20	69	78	47	71	85	28	24	41	45	74
73	34	34	23	27	34	38	37	33	27	26	35	38	33
74	31	36	26	22	29	34	33	30	30	32	33	32	28
75	49	35	23	39	47	47	51	47	31	27	42	47	47
76	54	34	22	46	54	48	56	52	31	25	43	48	53
DS	77	31	19	69	79	46	67	79	27	22	39	45	—

Table B–145. Pennsylvania Site 4 Right, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	54	12	4	14	27	15	40	37	7	5	10	11	34
02	15	16	6	8	11	13	14	11	8	7	11	14	10
03	5	10	11	5	6	9	5	4	9	9	11	10	5
04	19	6	4	30	28	12	18	23	6	4	10	13	19
05	28	7	4	19	40	13	27	31	6	4	9	11	27
06	20	9	5	13	21	16	19	19	7	6	10	13	17
07	40	9	3	11	27	12	41	35	6	5	8	9	21
08	37	8	3	12	24	14	28	48	6	5	10	11	24
73	8	9	6	7	9	11	8	7	9	7	12	12	8
74	7	11	7	5	7	10	6	6	10	13	11	10	6
75	11	8	5	11	14	12	10	12	9	6	17	15	11
76	13	9	5	14	18	12	12	13	7	6	12	18	16
DS	27	6	3	12	26	11	24	32	5	4	7	10	—

Table B–146. Pennsylvania Site 5 Left, IRI Filter.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	**95**	74	74	89	81	77	87	90	79	75	79	78	84
02	77	83	80	73	74	83	80	77	85	85	83	84	77
03	77	77	82	75	75	80	78	77	82	80	81	80	78
04	89	69	72	91	78	72	82	86	75	73	75	73	84
05	82	70	70	78	**95**	69	92	77	73	71	72	70	78
06	79	82	83	75	74	86	79	78	86	85	85	86	79
07	89	74	74	84	92	74	**97**	85	78	76	78	76	82
08	91	73	72	87	77	74	86	92	78	76	78	76	85
73	81	81	81	79	78	82	83	82	86	83	85	84	82
74	81	82	81	78	75	83	81	81	86	87	86	85	81
75	84	78	78	80	77	79	83	84	83	81	85	82	84
76	81	81	81	77	75	83	81	81	86	84	86	87	81
DS	89	72	73	88	81	73	87	87	77	75	78	75	—

Table B–147. Pennsylvania Site 5 Left, Long Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	98	79	79	91	80	78	84	96	82	82	83	81	96
02	79	96	94	73	86	95	86	77	96	95	94	96	79
03	79	93	95	73	86	92	86	79	94	94	94	94	79
04	91	73	72	86	72	71	76	90	75	75	77	75	88
05	80	85	86	72	99	85	96	75	88	89	89	88	80
06	78	95	92	71	85	94	85	76	94	94	93	95	77
07	85	85	86	76	96	85	99	81	88	89	89	88	84
08	96	77	78	90	75	75	81	96	79	80	81	79	94
73	82	95	94	75	88	94	88	80	97	97	96	97	81
74	82	95	94	76	89	93	89	80	97	97	97	97	82
75	83	94	94	77	89	93	89	81	96	97	97	96	83
76	81	96	94	75	88	95	88	79	97	97	97	98	81
DS	96	79	78	89	80	77	84	94	81	81	82	80	—

Table B–148. Pennsylvania Site 5 Left, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	91	68	67	83	75	75	82	84	74	69	72	68	75
02	75	73	68	74	71	71	76	77	75	73	73	71	74
03	73	64	70	76	70	67	72	71	70	64	66	65	70
04	84	67	70	88	76	72	81	80	73	69	71	69	77
05	75	61	60	72	92	61	88	70	66	61	62	61	68
06	82	68	70	78	70	75	75	79	75	71	72	72	76
07	81	65	63	76	88	65	94	78	71	66	67	65	70
08	86	69	65	81	73	72	81	87	75	71	73	71	75
73	81	68	69	79	75	71	80	80	77	69	73	71	77
74	80	70	68	79	71	73	76	81	75	78	74	72	77
75	82	66	65	78	72	68	78	79	72	67	74	70	75
76	82	68	68	78	70	73	76	81	76	71	75	77	78
DS	82	65	65	81	74	68	80	79	72	68	71	67	—

Table B–149. Pennsylvania Site 5 Left, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	65	43	34	34	26	48	34	49	43	45	49	39	45
02	27	41	29	22	40	28	38	33	41	36	37	31	34
03	22	27	39	22	32	30	25	25	40	28	32	32	30
04	41	45	42	53	37	44	38	41	47	45	44	41	50
05	25	25	23	21	70	24	48	23	33	26	26	25	32
06	35	29	33	25	39	47	35	39	47	37	34	39	39
07	32	27	23	22	48	27	58	36	39	34	30	31	32
08	48	40	31	26	30	40	43	62	48	46	43	41	37
73	26	29	31	20	40	34	32	30	50	31	35	37	37
74	30	33	26	22	34	32	34	35	39	53	35	34	38
75	33	33	30	23	35	30	35	38	43	35	50	40	43
76	35	30	33	24	36	37	36	39	49	37	43	49	44
DS	32	32	30	24	42	36	41	37	48	40	42	38	—

Table B–150. Pennsylvania Site 5 Right, IRI Filter.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	**97**	77	73	90	86	76	88	93	79	75	82	80	89
02	80	86	81	73	75	85	84	77	88	84	86	87	75
03	76	81	79	72	76	80	82	73	83	78	82	82	72
04	89	70	69	88	84	70	82	87	73	68	74	74	84
05	87	71	72	86	**96**	73	90	82	75	70	75	75	83
06	78	86	82	72	76	88	83	75	87	84	86	88	73
07	89	80	78	84	90	79	**98**	85	83	78	84	83	83
08	**94**	73	69	88	81	72	83	**95**	76	72	78	77	88
73	83	85	82	76	78	83	87	80	89	83	88	87	78
74	78	84	80	72	74	84	82	76	86	82	85	86	73
75	85	82	78	78	79	81	88	82	86	80	88	86	79
76	83	84	81	77	79	84	87	80	87	83	89	89	78
DS	90	72	68	86	81	70	82	87	74	69	76	74	—

Table B–151. Pennsylvania Site 5 Right, Long Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	98	82	84	89	87	78	87	98	83	83	84	83	91
02	83	97	95	78	82	93	88	81	97	97	96	97	76
03	85	94	96	80	86	90	90	83	95	95	96	95	78
04	89	78	79	84	79	73	81	89	79	78	80	78	84
05	88	82	85	80	99	79	95	83	83	82	84	83	82
06	78	94	91	73	79	94	84	76	93	94	92	93	72
07	88	87	90	81	95	84	99	84	88	88	89	88	82
08	98	80	82	89	83	75	84	98	81	81	83	81	90
73	84	97	95	79	83	93	89	82	97	97	97	97	77
74	83	97	95	79	83	93	88	81	97	97	97	97	77
75	85	96	96	80	84	91	89	83	97	96	98	97	78
76	84	97	95	79	83	93	89	82	97	97	97	97	77
DS	91	76	78	84	81	71	81	90	77	76	78	77	—

Table B–152. Pennsylvania Site 5 Right, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	95	74	64	86	86	75	89	90	76	69	79	76	79
02	79	77	68	72	75	76	84	76	80	71	77	77	75
03	70	69	66	69	72	69	76	67	72	65	69	70	68
04	87	66	62	86	87	70	83	83	70	63	72	72	74
05	87	67	64	88	92	70	88	83	71	64	72	72	76
06	80	75	67	75	78	79	84	76	78	72	78	79	76
07	91	75	68	86	88	76	96	87	80	72	81	80	84
08	91	69	60	83	81	69	85	91	72	66	75	73	75
73	83	76	67	77	79	73	87	80	80	70	79	77	79
74	76	73	65	69	71	74	80	74	76	70	75	76	72
75	86	71	62	78	79	70	85	83	75	67	77	75	78
76	84	73	65	77	79	75	87	81	77	71	79	80	79
DS	87	69	60	80	81	68	84	83	72	64	75	72	—

Table B–153. Pennsylvania Site 5 Right, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	68	43	20	27	38	41	56	52	46	36	48	42	29
02	30	41	21	16	31	27	41	33	41	29	37	31	23
03	17	28	25	17	28	22	24	15	32	23	25	24	14
04	33	30	22	44	52	32	46	25	38	28	34	35	20
05	34	29	21	30	62	33	54	29	36	26	34	36	21
06	33	30	19	20	37	38	42	32	34	30	32	35	16
07	50	34	19	26	54	32	74	49	42	33	40	42	22
08	50	35	15	15	27	30	50	63	39	34	41	41	23
73	28	34	20	17	31	25	39	30	43	27	38	33	22
74	28	29	17	16	28	27	37	31	33	33	35	34	20
75	32	30	15	14	28	23	39	35	37	28	43	37	27
76	34	26	15	16	31	27	42	35	34	30	39	45	24
DS	41	37	16	18	33	25	40	38	37	30	45	41	—

Table B–154. Pennsylvania Site 6 Left, IRI Filter.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	**94**	85	78	87	91	76	93	88	84	80	86	83	88
02	90	86	80	86	89	77	89	87	86	84	85	84	83
03	83	78	89	84	85	71	88	75	82	78	80	80	84
04	88	87	85	**95**	88	80	89	89	86	84	80	89	84
05	93	83	81	86	**96**	75	92	86	86	81	86	82	85
06	82	81	77	83	82	75	82	83	79	81	78	80	76
07	**94**	82	81	86	92	75	**96**	86	85	81	87	82	89
08	90	85	75	87	88	79	87	**95**	84	86	85	85	79
73	90	82	80	84	89	75	90	83	86	80	85	82	86
74	89	84	80	86	88	77	90	87	85	89	86	84	84
75	89	79	74	80	85	73	88	82	82	79	85	79	86
76	89	84	82	87	88	77	91	86	85	84	86	88	85
DS	86	75	75	80	84	69	88	76	77	74	79	76	—

Table B–155. Pennsylvania Site 6 Left, Long Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	98	82	86	78	85	82	90	96	85	85	88	87	93
02	82	94	89	81	90	91	85	79	94	93	90	91	79
03	88	88	93	80	91	88	91	84	91	91	92	93	84
04	78	80	80	75	80	80	77	76	82	81	80	81	75
05	85	88	91	80	99	86	94	80	91	91	91	92	83
06	82	91	89	80	88	89	85	80	92	92	89	90	79
07	90	83	89	77	93	83	99	86	87	87	89	90	88
08	96	78	83	76	80	79	86	98	81	82	85	85	94
73	86	93	93	82	92	91	88	83	95	94	93	94	82
74	86	91	92	82	92	91	89	83	94	94	93	94	82
75	90	88	93	80	91	88	91	87	92	92	94	94	85
76	89	89	94	82	92	89	91	86	93	93	94	95	85
DS	94	77	83	74	82	78	88	93	81	81	83	83	—

Table B–156. Pennsylvania Site 6 Left, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	94	85	75	87	92	74	94	87	83	79	85	83	85
02	90	84	78	84	88	73	89	84	84	81	84	81	84
03	81	73	87	81	82	66	87	70	78	74	77	76	84
04	88	86	82	95	89	77	89	88	86	82	80	88	84
05	94	81	80	86	95	73	91	84	85	81	85	79	85
06	82	78	74	80	81	71	82	79	77	77	76	76	75
07	93	79	79	85	91	72	96	83	82	80	84	79	88
08	90	84	73	86	87	77	86	95	83	85	83	83	77
73	89	79	78	83	88	72	90	80	85	78	83	79	86
74	90	80	77	83	87	72	90	84	81	87	84	80	83
75	86	76	72	78	83	69	86	79	78	76	83	76	84
76	89	80	80	85	87	73	90	83	83	81	84	86	85
DS	83	73	73	78	82	66	86	74	75	72	77	74	—

Table B–157. Pennsylvania Site 6 Left, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	81	64	33	52	75	47	70	67	60	57	66	64	63
02	43	60	36	29	49	38	45	43	53	50	52	48	41
03	25	33	64	24	34	27	34	21	43	41	38	40	30
04	65	62	51	68	71	44	69	50	61	55	63	68	80
05	65	51	45	40	85	45	72	54	58	56	54	50	48
06	40	46	35	29	45	42	42	39	49	45	50	42	40
07	58	49	47	41	72	44	74	50	58	55	54	51	43
08	60	53	31	30	55	45	50	78	51	61	60	52	41
73	39	47	40	30	47	39	44	36	64	44	52	48	40
74	40	44	40	27	44	35	43	43	46	68	50	46	34
75	41	44	33	26	46	39	43	42	50	47	62	47	44
76	41	46	40	30	48	36	46	40	52	48	53	63	45
DS	40	42	36	34	52	37	51	34	47	39	50	48	—

Table B–158. Pennsylvania Site 6 Right, IRI Filter.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	**95**	87	79	77	84	82	88	89	86	81	86	85	76
02	90	88	81	77	85	83	88	88	87	84	87	85	74
03	83	79	85	75	82	78	84	77	80	78	80	81	74
04	78	77	75	79	86	81	87	81	77	80	76	79	66
05	86	88	85	86	**96**	89	**95**	89	88	89	87	90	75
06	87	88	83	82	89	89	92	90	88	87	87	89	72
07	89	89	85	85	**95**	88	**98**	92	89	88	90	90	76
08	90	86	77	80	88	85	91	**96**	86	85	89	87	72
73	90	85	81	77	84	83	87	86	88	81	87	85	75
74	89	87	81	80	87	85	90	90	85	90	88	87	75
75	91	82	78	74	81	81	84	85	83	80	87	82	77
76	90	85	83	79	87	84	89	89	86	84	87	89	77
DS	76	68	67	64	72	67	74	71	68	68	70	70	—

Table B–159. Pennsylvania Site 6 Right, Long Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	98	86	87	77	91	84	88	95	86	85	90	88	79
02	86	96	92	84	88	93	91	83	96	96	93	94	70
03	89	91	92	81	91	89	91	85	92	92	93	93	73
04	77	84	82	81	79	83	81	75	84	84	81	83	64
05	91	87	90	79	99	85	96	89	88	88	91	91	77
06	84	93	90	84	86	92	89	82	93	93	90	92	68
07	88	89	91	81	96	87	99	85	91	90	93	93	74
08	95	82	84	75	88	80	85	98	83	83	87	86	77
73	87	95	93	84	89	92	92	84	95	95	94	95	71
74	87	95	93	85	89	93	92	84	95	96	93	95	71
75	91	91	92	80	92	90	93	88	93	92	95	94	74
76	90	93	93	83	92	91	93	87	94	94	95	95	74
DS	80	69	71	64	76	67	73	77	70	69	73	73	—

Table B–160. Pennsylvania Site 6 Right, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	94	86	76	78	85	81	89	88	86	81	84	83	75
02	90	87	77	76	83	81	87	86	83	82	84	82	76
03	81	75	83	74	79	74	81	73	76	74	77	77	75
04	80	77	75	81	86	81	88	82	77	80	76	79	67
05	87	86	83	86	95	87	95	90	86	87	87	88	77
06	89	85	80	81	87	87	91	89	86	84	86	86	74
07	91	86	83	85	95	87	98	93	87	87	89	88	77
08	90	85	74	80	87	85	91	96	85	84	87	86	72
73	90	83	78	77	83	81	86	84	86	78	85	82	76
74	90	83	78	78	85	81	88	88	81	88	85	83	77
75	88	78	74	73	80	78	83	83	80	78	85	79	77
76	90	82	79	79	85	81	88	86	83	81	85	87	79
DS	75	67	67	65	72	67	74	70	66	68	69	69	—

Table B–161. Pennsylvania Site 6 Right, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	81	68	37	48	64	60	66	57	69	55	62	65	47
02	42	64	32	28	41	44	49	46	52	51	48	49	36
03	23	31	54	21	29	29	33	21	36	38	36	37	31
04	58	49	45	60	63	55	71	44	52	58	57	56	47
05	64	49	44	46	78	52	72	54	53	61	60	59	60
06	43	48	34	31	45	59	54	48	55	49	59	53	38
07	61	48	40	42	72	52	88	61	54	58	60	58	51
08	53	50	27	26	42	49	54	83	54	55	55	57	34
73	42	50	34	29	42	47	50	42	67	43	54	52	33
74	39	44	33	24	37	38	45	47	40	66	48	46	34
75	39	41	30	25	38	46	47	44	48	47	62	48	35
76	40	43	33	28	42	42	49	44	50	48	51	64	38
DS	31	33	31	25	39	33	45	32	34	39	37	40	—

Table B–162. Pennsylvania Site 7 Left, IRI Filter.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	**94**	84	80	89	84	73	89	89	85	86	84	85	75
02	89	84	80	86	83	71	86	83	83	84	83	83	73
03	80	73	89	81	74	63	80	75	76	76	75	79	77
04	90	81	83	91	82	72	87	84	84	84	81	85	73
05	86	87	79	85	**95**	70	83	76	83	81	82	80	69
06	75	68	68	73	67	60	72	73	70	72	70	72	65
07	90	80	82	87	83	70	87	85	82	83	83	83	75
08	89	76	75	82	75	68	83	92	78	81	82	81	76
73	87	78	82	85	78	70	85	84	82	82	82	82	76
74	87	77	80	84	76	69	84	86	80	84	81	82	78
75	87	77	78	82	76	67	83	85	79	80	81	80	77
76	85	76	81	84	75	68	82	84	79	80	79	84	77
DS	75	66	70	73	67	59	73	74	69	70	70	70	—

Table B–163. Pennsylvania Site 7 Left, Long Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	97	83	87	66	85	77	92	96	83	83	87	83	84
02	84	92	91	71	92	86	86	80	92	92	91	91	72
03	88	90	94	69	91	84	90	85	91	90	92	90	76
04	66	70	69	58	70	68	67	65	71	71	68	72	58
05	85	91	91	70	99	83	91	80	91	90	91	89	72
06	78	86	85	68	84	81	80	75	86	87	84	87	68
07	92	85	89	67	91	79	98	88	86	85	89	84	79
08	96	79	84	65	80	74	88	97	82	81	84	80	85
73	85	91	92	71	92	86	88	83	92	92	92	92	74
74	84	91	91	71	90	86	86	82	92	92	91	92	73
75	88	89	92	68	91	83	90	85	91	90	92	89	75
76	83	91	91	72	90	87	85	81	92	92	90	93	73
DS	85	71	75	58	72	67	79	84	73	72	74	72	—

Table B–164. Pennsylvania Site 7 Left, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	93	83	76	89	85	70	85	89	83	85	82	82	71
02	88	81	78	86	82	68	82	83	80	81	81	81	71
03	76	69	86	80	73	59	75	71	72	72	71	75	76
04	89	80	82	92	83	70	85	85	83	84	81	84	72
05	87	87	78	86	95	69	83	77	83	81	81	81	68
06	73	64	65	72	66	56	69	72	67	69	67	69	63
07	86	78	79	85	83	66	82	82	78	79	80	80	71
08	88	75	73	83	76	66	81	90	76	79	81	80	72
73	85	75	80	84	77	66	81	82	80	79	79	80	75
74	85	75	78	83	76	65	80	83	76	82	78	79	76
75	85	74	75	81	75	63	79	82	76	77	79	78	76
76	82	73	79	83	74	64	78	81	75	77	77	82	76
DS	72	63	68	71	66	56	69	70	66	67	67	67	—

Table B–165. Pennsylvania Site 7 Left, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	67	52	32	33	54	42	33	49	53	61	55	52	30
02	43	53	38	26	49	34	26	35	48	48	48	49	46
03	18	30	54	19	32	21	17	14	36	35	31	38	36
04	45	47	49	50	58	39	32	32	51	56	48	55	37
05	56	56	48	38	82	40	40	39	55	54	56	60	54
06	33	33	27	21	34	31	20	28	37	37	35	39	41
07	37	44	34	27	40	32	23	28	44	43	45	45	35
08	47	39	25	19	34	32	22	52	38	43	47	45	35
73	38	42	39	26	45	34	25	29	54	45	47	47	51
74	38	39	35	25	43	31	24	31	42	56	44	45	47
75	40	39	31	22	40	29	23	34	44	44	53	43	48
76	33	38	35	25	40	30	22	27	41	42	40	54	46
DS	30	31	29	20	35	26	20	23	36	33	35	36	—

Table B–166. Pennsylvania Site 7 Right, IRI Filter.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	91	85	76	85	87	85	88	87	82	84	83	83	78
02	88	85	79	83	87	82	87	86	83	82	83	83	79
03	76	73	86	80	84	74	81	76	76	74	74	78	81
04	85	82	81	91	91	83	91	82	82	82	80	85	78
05	87	81	84	89	**96**	82	93	88	82	81	83	86	86
06	87	83	81	85	89	85	89	86	84	83	83	85	80
07	89	84	84	90	93	85	**94**	87	84	83	84	88	82
08	88	80	74	81	86	80	85	**95**	79	79	82	81	83
73	85	80	80	82	87	81	86	86	83	79	81	81	82
74	86	82	80	84	88	82	87	86	82	84	82	83	81
75	84	79	77	80	86	79	84	86	80	78	81	80	82
76	85	80	82	85	91	81	88	87	81	80	81	86	82
DS	78	72	74	76	83	73	80	81	74	72	74	75	—

Table B–167. Pennsylvania Site 7 Right, Long Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	96	87	90	70	89	84	89	93	87	87	90	88	87
02	88	93	92	71	84	92	87	82	93	92	92	92	78
03	91	91	95	71	88	90	91	86	93	92	93	93	82
04	70	71	71	61	69	72	71	67	72	72	70	73	64
05	90	83	87	69	99	82	96	89	85	86	86	87	86
06	85	93	91	73	83	94	86	81	93	92	91	93	77
07	89	86	90	70	96	85	98	85	88	89	89	90	82
08	93	82	85	67	89	80	85	98	83	83	85	83	92
73	89	93	94	72	86	92	89	84	94	93	93	94	80
74	88	92	93	72	87	92	90	84	93	92	92	93	80
75	91	91	93	71	88	90	90	86	92	92	92	92	82
76	89	92	94	73	88	92	91	84	94	93	93	95	81
DS	87	77	81	64	85	76	82	92	79	79	80	80	—

Table B–168. Pennsylvania Site 7 Right, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	90	83	73	84	86	83	87	87	79	83	80	81	76
02	86	82	76	83	86	78	85	86	79	78	80	80	80
03	72	70	83	78	82	70	78	73	72	71	71	74	80
04	85	81	80	93	92	82	91	84	81	81	81	85	79
05	85	79	81	89	95	79	92	88	79	78	80	84	86
06	85	79	77	85	88	82	87	87	81	80	80	82	80
07	87	82	81	90	92	82	92	88	82	81	83	86	82
08	87	79	72	81	87	79	86	94	78	77	81	81	81
73	82	76	77	81	86	78	84	84	80	76	79	78	82
74	84	78	77	83	87	79	86	86	79	81	79	80	81
75	82	75	74	79	84	75	82	85	77	74	79	77	83
76	82	77	79	84	89	78	86	85	78	77	79	84	82
DS	76	70	71	76	82	71	80	79	72	70	72	73	—

Table B–169. Pennsylvania Site 7 Right, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	69	50	32	35	45	48	45	49	51	58	54	53	40
02	41	54	32	27	43	39	44	47	45	45	47	48	51
03	19	28	51	22	33	26	29	19	35	35	32	37	39
04	43	45	46	58	65	47	57	39	51	52	50	56	51
05	43	44	37	39	69	43	58	47	47	45	47	55	63
06	40	41	32	28	45	49	45	50	48	47	44	49	56
07	45	45	35	37	58	44	55	50	47	47	48	56	56
08	47	41	24	21	38	41	42	75	41	44	46	50	48
73	35	39	34	26	41	40	41	41	52	42	47	44	51
74	36	38	33	26	42	39	42	45	42	56	43	46	48
75	38	39	30	24	39	35	40	46	45	42	52	43	50
76	34	39	33	28	45	38	43	42	41	44	42	60	46
DS	35	37	33	25	45	39	45	43	43	39	42	42	—

Table B–170. Pennsylvania Site 8 Left, IRI Filter.

Correlation Reference	Correlated Device 01	02	03	04	05	06	07	08	73	74	75	76	DS
01	93	73	72	77	84	67	66	84	80	78	78	74	78
02	79	73	74	74	80	66	63	77	75	74	74	71	70
03	76	68	83	74	80	66	58	69	73	69	70	65	75
04	78	70	73	81	77	72	64	78	75	73	71	73	75
05	86	75	81	78	**96**	66	68	81	79	77	79	71	74
06	71	62	67	73	66	74	56	68	67	67	67	67	72
07	68	65	64	66	68	60	60	70	67	69	67	64	60
08	86	74	71	79	81	69	68	88	79	79	79	76	74
73	84	70	74	75	79	66	63	77	77	75	75	70	77
74	85	69	71	74	77	67	63	78	75	77	75	71	77
75	85	68	70	73	77	65	61	78	75	74	76	69	77
76	80	69	69	76	74	69	61	78	74	74	73	73	74
DS	77	63	68	72	71	65	57	72	68	69	68	66	—

Table B–171. Pennsylvania Site 8 Left, Long Wavelengths.

Correlation Reference	Correlated Device 01	02	03	04	05	06	07	08	73	74	75	76	DS
01	96	80	82	41	83	77	86	94	80	81	82	80	92
02	81	82	85	41	86	81	80	78	85	84	83	82	79
03	83	84	88	41	88	82	82	80	86	85	85	83	81
04	41	41	41	32	41	43	37	40	42	42	41	42	40
05	83	86	89	41	99	81	87	79	89	88	87	85	80
06	78	81	83	43	82	88	78	75	84	84	83	82	79
07	86	79	81	37	87	76	90	82	81	81	81	80	83
08	95	77	78	40	79	74	82	95	77	78	79	77	91
73	82	85	87	43	90	83	82	79	87	87	86	84	79
74	82	84	86	43	88	83	83	79	87	86	85	84	80
75	83	83	85	41	86	82	82	80	85	85	84	83	81
76	81	82	83	42	85	82	81	79	84	84	83	82	80
DS	93	77	79	40	79	78	82	92	78	79	79	78	—

Table B–172. Pennsylvania Site 8 Left, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	93	70	69	79	83	65	57	82	78	76	77	73	76
02	80	72	71	75	79	63	53	74	73	71	72	68	71
03	72	64	81	72	77	61	48	64	68	64	65	61	74
04	80	70	73	85	79	73	57	78	76	74	72	74	77
05	86	72	79	79	96	63	58	78	76	72	76	69	73
06	69	58	63	73	64	71	47	65	64	64	64	64	72
07	59	59	57	60	58	54	51	63	61	62	61	58	52
08	84	71	67	78	79	67	58	86	76	77	77	74	71
73	83	67	70	75	78	63	53	74	76	71	73	68	77
74	84	66	66	75	75	64	53	75	71	75	72	69	78
75	83	65	65	72	75	62	52	74	71	70	74	66	77
76	80	65	66	76	72	66	52	75	70	71	70	72	75
DS	74	60	64	72	69	61	48	68	64	66	65	64	—

Table B–173. Pennsylvania Site 8 Left, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	75	45	30	39	51	39	13	55	54	54	55	53	55
02	45	52	36	29	49	31	9	36	45	43	45	42	47
03	21	29	58	21	42	22	5	17	34	28	29	27	33
04	51	44	41	56	55	46	12	44	54	53	48	53	61
05	49	44	48	34	84	32	12	36	47	42	46	41	47
06	34	29	27	26	33	43	8	28	36	36	35	35	43
07	18	30	20	19	12	23	13	16	31	32	32	28	14
08	60	42	28	32	42	36	11	54	49	51	52	48	40
73	44	39	36	29	48	33	9	36	56	44	48	41	47
74	47	37	28	27	41	33	9	38	43	57	43	43	51
75	45	37	29	26	40	30	9	37	45	42	54	40	45
76	42	35	28	27	37	32	8	36	40	42	41	51	52
DS	37	32	29	29	39	30	8	31	36	40	37	39	—

Table B–174. Pennsylvania Site 8 Right, IRI Filter.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	88	69	64	70	75	68	80	81	74	72	73	70	72
02	75	70	66	67	73	67	73	71	72	68	69	68	64
03	66	61	71	63	75	60	72	67	66	59	61	59	68
04	71	64	65	78	81	77	79	72	69	65	66	69	69
05	76	65	74	79	93	73	89	79	73	66	68	68	77
06	75	64	65	79	81	79	81	75	72	69	69	70	72
07	80	66	69	77	89	73	**94**	87	74	70	71	71	84
08	81	65	64	70	78	69	87	88	74	71	72	70	79
73	77	65	68	68	77	66	81	79	74	68	70	67	73
74	77	64	62	66	72	66	78	77	71	70	70	68	70
75	78	64	64	66	73	66	78	78	72	68	71	66	71
76	76	65	63	70	75	70	79	77	72	70	70	71	71
DS	70	57	61	66	75	64	82	76	64	62	62	63	—

Table B–175. Pennsylvania Site 8 Right, Long Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	92	81	83	47	79	81	81	86	83	85	83	82	80
02	82	86	84	51	76	82	79	75	86	86	86	85	73
03	83	83	84	49	79	83	82	77	85	85	84	83	75
04	47	51	49	38	47	51	48	45	50	50	50	51	44
05	80	75	79	47	98	85	95	83	79	79	76	79	84
06	82	81	83	51	86	90	88	79	85	85	83	85	80
07	82	78	81	48	95	87	97	81	82	83	79	81	82
08	86	74	76	45	83	78	81	93	76	77	76	76	91
73	84	85	85	50	80	85	83	78	86	87	86	85	75
74	86	86	85	50	80	86	84	79	87	88	87	86	76
75	84	86	84	50	76	84	79	77	86	87	87	85	74
76	82	85	84	51	80	85	82	77	85	86	85	85	75
DS	80	72	74	45	84	78	82	90	74	76	73	74	—

Table B–176. Pennsylvania Site 8 Right, Medium Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	89	65	57	72	73	66	82	79	71	68	71	67	73
02	74	66	61	67	71	61	75	72	66	61	64	60	65
03	59	54	69	61	70	53	66	60	58	50	53	50	66
04	73	66	64	84	83	78	83	72	70	66	68	69	70
05	74	62	69	79	90	69	86	76	68	61	65	63	75
06	75	59	60	78	79	77	83	76	67	64	66	64	74
07	82	64	62	78	86	70	93	87	70	66	69	68	83
08	79	61	55	69	73	65	84	87	68	66	68	65	78
73	73	59	60	67	73	61	78	76	70	61	65	61	75
74	75	58	54	65	68	61	77	76	64	66	64	61	72
75	75	57	55	64	68	60	77	77	65	61	68	60	73
76	75	60	56	69	73	65	81	76	67	64	65	68	73
DS	69	54	55	67	72	62	80	74	60	59	60	60	—

Table B–177. Pennsylvania Site 8 Right, Short Wavelengths.

Correlation Reference	Correlated Device												
	01	02	03	04	05	06	07	08	73	74	75	76	DS
01	74	44	26	42	44	47	66	56	52	49	55	49	62
02	45	50	32	34	42	38	52	48	41	38	41	40	48
03	20	28	53	26	39	26	32	24	31	23	26	23	31
04	53	51	44	64	66	59	71	48	55	49	54	53	55
05	46	43	44	47	73	45	63	43	47	38	44	43	49
06	47	38	30	41	47	57	59	55	45	42	45	44	57
07	62	44	32	47	63	48	84	68	50	46	52	50	62
08	54	38	22	33	36	40	58	68	43	43	47	45	49
73	45	38	32	36	44	41	55	51	56	40	49	43	52
74	48	36	24	33	38	40	55	55	42	52	44	42	53
75	46	34	25	31	37	38	52	53	45	39	55	40	48
76	47	37	24	34	41	40	57	56	44	41	45	55	56
DS	45	34	26	36	45	40	62	52	39	40	42	43	—

Table B–178. South Dakota Site 1 Left, IRI Filter.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	81	74	71	71	67	71	69	33	63	74	81
02	68	83	71	68	75	67	77	25	61	73	83
03	67	75	70	67	70	63	72	25	60	70	76
04	67	68	68	67	68	64	70	26	56	69	70
05	62	71	64	64	**94**	56	93	23	53	65	70
06	70	67	67	64	60	73	64	31	61	66	68
08	64	72	66	66	93	60	**95**	25	54	67	71
10	37	28	29	28	25	34	27	90	26	28	33
11	68	67	65	61	57	65	59	25	70	66	68
12	70	73	70	68	69	66	71	25	61	71	77
DS	75	83	75	70	74	68	75	29	62	76	—

Table B–179. South Dakota Site 1 Left, Long Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	98	77	75	77	80	79	82	86	71	77	87
02	76	97	95	94	87	94	86	67	64	96	81
03	74	95	95	94	89	92	87	64	66	95	79
04	77	94	94	94	90	93	88	66	63	95	82
05	79	88	89	90	98	90	97	66	69	89	84
06	79	94	93	93	90	95	88	69	66	94	83
08	81	86	87	88	97	88	98	68	71	87	85
10	86	67	64	67	66	69	68	94	56	66	81
11	72	65	66	64	69	67	72	56	84	66	58
12	77	96	95	95	89	94	87	66	65	96	81
DS	87	81	79	82	85	83	85	81	57	82	—

Table B–180. South Dakota Site 1 Left, Medium Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	71	69	60	56	61	55	64	22	56	62	74
02	60	77	60	56	67	57	68	18	57	62	78
03	61	68	60	56	61	52	62	19	55	59	71
04	60	56	58	56	57	52	58	18	51	57	58
05	53	60	51	50	92	44	92	16	46	52	63
06	61	57	56	52	49	61	52	24	56	54	55
08	55	61	52	52	92	47	93	17	47	53	63
10	26	22	21	20	18	25	19	86	22	20	24
11	63	67	60	54	53	56	55	21	60	60	69
12	63	62	60	57	58	54	60	17	56	60	65
DS	64	78	63	58	69	55	70	20	58	65	—

Table B–181. South Dakota Site 1 Left, Short Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	37	27	22	15	30	14	33	8	19	18	26
02	21	42	25	19	34	15	35	7	21	23	38
03	22	30	27	16	28	12	29	7	19	18	32
04	22	19	25	21	21	13	22	9	19	22	18
05	17	22	18	14	66	8	63	5	15	15	24
06	21	15	19	13	11	22	14	8	16	13	11
08	20	22	18	14	63	10	73	5	15	15	20
10	10	10	9	7	9	7	10	47	8	8	9
11	18	24	18	11	21	9	21	7	20	14	23
12	23	23	24	22	23	13	23	9	19	24	25
DS	19	38	27	18	35	11	34	7	20	25	—

Table B–182. South Dakota Site 1 Right, IRI Filter.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	83	79	82	40	63	78
05	73	**95**	92	42	63	84
08	77	92	**95**	42	65	79
10	36	40	39	88	31	45
11	66	68	71	34	70	64
DS	72	82	78	44	60	—

Table B–183. South Dakota Site 1 Right, Long Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	97	90	92	73	61	87
05	90	99	97	64	67	83
08	92	97	99	62	65	80
10	73	64	62	94	57	85
11	60	67	65	58	85	68
DS	86	82	80	86	68	—

Table B–184. South Dakota Site 1 Right, Medium Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	72	71	74	28	56	72
05	61	92	90	27	57	75
08	65	90	92	29	59	76
10	27	32	33	83	26	34
11	63	66	69	28	61	62
DS	62	77	74	29	53	—

Table B–185. South Dakota Site 1 Right, Short Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	40	29	34	8	23	23
05	25	74	68	6	22	30
08	28	68	77	6	23	25
10	12	14	12	50	10	11
11	21	22	25	6	19	17
DS	22	31	28	5	18	—

Table B–186. South Dakota Site 2 Left, IRI Filter.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	30	24	20	25	21	25	24	18	23	21	24
02	21	49	15	22	46	20	51	28	20	18	50
03	21	18	16	20	15	19	17	12	19	18	16
04	22	22	18	25	21	21	23	15	22	19	21
05	19	43	14	19	91	17	88	32	16	14	75
06	25	20	18	21	18	23	21	15	23	20	19
08	21	48	15	22	88	19	93	33	18	15	78
10	16	29	11	14	34	14	35	71	14	12	33
11	22	24	17	23	18	22	21	15	21	20	22
12	22	18	18	19	15	20	16	12	21	19	16
DS	20	50	14	21	75	19	76	30	19	16	—

Table B–187. South Dakota Site 2 Left, Long Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	89	64	61	65	76	67	76	72	59	63	73
02	64	94	81	86	80	82	80	68	66	83	83
03	60	82	75	78	77	76	78	63	61	76	76
04	64	86	78	83	80	80	80	68	62	79	82
05	76	80	78	80	98	83	98	75	73	78	81
06	67	82	77	80	83	83	83	71	69	79	82
08	76	81	78	80	98	83	99	76	72	78	81
10	72	68	63	67	75	70	75	86	57	65	82
11	59	66	61	63	72	69	72	57	74	64	59
12	62	83	76	79	78	79	78	65	64	77	79
DS	72	82	75	82	81	82	81	82	59	79	—

Table B–188. South Dakota Site 2 Left, Medium Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	19	17	12	15	11	15	14	9	14	13	14
02	13	36	9	14	29	13	34	16	13	12	34
03	14	13	11	13	9	13	10	7	13	13	10
04	14	14	11	17	11	14	13	8	15	14	12
05	9	25	7	9	81	9	78	16	9	7	59
06	16	13	12	14	10	17	12	9	15	14	11
08	11	29	8	11	78	11	87	17	11	8	71
10	8	15	6	7	18	8	19	59	8	6	17
11	14	17	12	16	11	15	13	9	14	14	15
12	16	12	12	14	8	14	10	8	16	15	9
DS	11	34	8	12	65	11	72	14	11	9	—

Table B–189. South Dakota Site 2 Left, Short Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	13	8	7	7	4	8	5	6	8	6	4
02	4	15	4	7	9	5	11	7	4	7	10
03	8	7	9	7	3	6	4	6	8	7	4
04	7	7	7	11	4	9	4	5	8	10	3
05	2	6	2	2	46	2	37	3	2	2	23
06	9	5	6	9	3	11	3	5	8	9	2
08	3	7	2	3	37	2	57	3	2	3	31
10	3	7	3	4	6	3	6	19	4	3	5
11	7	8	6	6	3	6	4	7	9	6	4
12	9	7	8	10	3	9	4	5	9	12	3
DS	2	10	2	3	13	2	23	2	2	3	—

Table B–190. South Dakota Site 2 Right, IRI Filter.

Correlation Reference	Correlated Device 01	05	08	10	11	DS
01	47	37	36	24	39	39
05	34	**94**	93	45	38	84
08	33	93	93	46	37	83
10	23	47	48	84	20	54
11	35	41	40	22	41	39
DS	35	86	85	51	34	—

Table B–191. South Dakota Site 2 Right, Long Wavelengths.

Correlation Reference	Correlated Device 01	05	08	10	11	DS
01	93	75	76	70	66	80
05	75	98	98	79	85	88
08	76	98	98	79	85	89
10	69	79	79	93	67	86
11	66	85	85	67	87	77
DS	80	88	89	86	77	—

Table B–192. South Dakota Site 2 Right, Medium Wavelengths.

Correlation Reference	Correlated Device 01	05	08	10	11	DS
01	28	23	22	11	27	23
05	19	90	87	25	22	78
08	17	87	88	26	20	74
10	10	28	29	72	10	29
11	23	27	25	12	27	26
DS	18	83	80	26	20	—

Table B–193. South Dakota Site 2 Right, Short Wavelengths.

Correlation Reference	Correlated Device 01	05	08	10	11	DS
01	12	5	5	5	8	5
05	3	59	53	3	3	37
08	3	53	57	3	3	32
10	3	7	7	17	3	6
11	6	5	4	5	10	4
DS	3	26	26	3	2	—

Table B–194. South Dakota Site 3 Left, IRI Filter.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	42	40	30	24	40	25	44	30	32	26	39
02	35	64	29	22	69	23	74	31	31	24	55
03	32	34	29	24	35	23	37	22	30	26	32
04	28	22	27	29	26	24	27	18	26	27	22
05	37	66	31	24	91	22	91	38	32	27	62
06	29	23	26	24	24	28	26	17	28	24	19
08	40	71	33	25	91	24	**95**	37	34	27	65
10	28	34	20	17	40	16	39	73	22	18	36
11	33	36	29	22	36	24	39	23	32	24	34
12	30	24	29	27	29	24	30	19	27	28	24
DS	34	55	27	22	67	19	70	33	29	24	—

Table B–195. South Dakota Site 3 Left, Long Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	94	70	63	72	76	69	77	83	51	68	77
02	70	97	92	90	83	93	82	59	80	93	69
03	63	92	91	85	78	87	78	51	81	88	60
04	72	90	86	90	85	89	84	61	73	88	70
05	76	83	79	85	98	81	98	63	67	81	60
06	69	93	88	89	81	91	81	58	78	91	68
08	77	82	78	85	98	81	99	62	67	80	59
10	83	58	51	61	63	58	62	93	40	57	80
11	51	80	81	72	67	77	67	40	83	77	48
12	68	93	88	88	81	91	80	57	78	90	67
DS	76	69	61	70	60	68	60	80	48	68	—

Table B–196. South Dakota Site 3 Left, Medium Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	29	31	21	15	28	16	33	18	22	17	27
02	23	54	20	15	57	16	64	22	22	17	46
03	24	27	22	18	26	16	29	15	23	19	24
04	20	15	21	21	19	17	20	11	20	19	14
05	23	52	21	16	86	13	85	25	22	18	54
06	21	16	19	17	16	21	18	11	21	17	12
08	27	57	23	17	85	15	92	25	24	19	56
10	15	25	13	9	29	9	29	60	14	11	23
11	24	29	22	15	28	17	30	17	24	17	26
12	21	17	22	19	21	17	22	13	21	21	16
DS	21	46	18	14	61	12	64	19	20	16	—

Table B–197. South Dakota Site 3 Left, Short Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	15	12	8	4	6	5	10	9	8	5	9
02	6	27	6	5	20	4	31	5	5	5	20
03	10	11	11	6	9	5	11	8	9	6	8
04	10	5	11	12	5	9	6	6	9	10	4
05	4	15	5	4	53	2	49	4	5	4	19
06	11	4	10	9	3	12	4	6	9	9	3
08	6	21	7	4	49	3	69	4	5	5	23
10	6	10	5	4	8	4	8	20	6	4	9
11	8	9	8	4	8	5	9	8	10	6	7
12	10	5	10	10	6	9	7	6	10	11	4
DS	4	20	4	4	24	3	37	4	4	4	—

Table B–198. South Dakota Site 3 Right, IRI Filter.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	45	41	40	24	35	41
05	37	92	91	40	33	76
08	36	91	**96**	41	32	72
10	22	42	43	80	19	45
11	35	37	36	21	33	36
DS	36	81	77	45	31	—

Table B–199. South Dakota Site 3 Right, Long Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	92	75	77	81	73	86
05	74	99	97	57	85	66
08	76	97	99	58	85	68
10	80	56	58	90	57	84
11	73	85	85	57	84	65
DS	85	67	68	84	65	—

Table B–200. South Dakota Site 3 Right, Medium Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	34	33	32	16	26	32
05	27	90	87	30	23	76
08	26	87	93	30	22	70
10	13	33	34	71	13	34
11	26	29	28	15	24	29
DS	25	81	78	32	23	—

Table B–201. South Dakota Site 3 Right, Short Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	17	7	10	6	8	9
05	5	63	60	6	5	38
08	6	60	72	7	5	39
10	4	13	15	25	4	12
11	7	7	8	7	12	8
DS	5	35	38	5	4	—

Table B–202. South Dakota Site 4 Left, IRI Filter.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	30	26	22	22	25	19	27	19	21	20	27
02	23	36	20	19	40	18	42	24	21	21	38
03	23	23	20	19	22	19	24	13	21	20	23
04	26	19	21	23	20	19	21	12	24	20	19
05	22	37	20	18	89	16	89	27	18	18	74
06	21	18	19	19	18	20	18	14	20	20	16
08	24	39	21	19	89	17	92	28	19	19	77
10	17	24	12	12	29	14	30	62	13	13	33
11	23	25	21	21	21	19	22	14	29	22	23
12	22	21	21	20	20	20	21	14	23	23	19
DS	24	38	20	19	80	16	81	29	20	19	—

Table B–203. South Dakota Site 4 Left, Long Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	92	67	62	68	69	69	70	79	53	69	88
02	67	95	89	89	86	85	85	56	80	89	64
03	62	89	86	85	82	82	82	50	76	85	57
04	68	89	86	88	86	86	85	57	75	88	65
05	69	86	82	86	99	87	98	56	73	86	63
06	69	85	83	86	87	87	86	57	75	88	66
08	70	85	82	85	98	86	98	56	72	85	63
10	79	56	49	57	54	57	54	89	49	57	89
11	52	80	76	74	73	75	72	48	80	76	49
12	69	89	85	88	86	88	85	58	77	90	66
DS	87	63	57	65	62	65	63	89	51	65	—

Table B–204. South Dakota Site 4 Left, Medium Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	20	20	15	15	18	12	20	11	15	13	19
02	15	29	14	14	30	12	32	15	15	15	28
03	17	18	15	14	17	13	18	9	16	15	18
04	19	14	16	18	14	13	15	8	18	15	14
05	14	26	13	12	84	10	85	14	12	11	64
06	14	12	13	13	12	14	12	9	14	15	10
08	15	27	14	12	85	11	89	15	13	12	68
10	9	13	7	6	18	8	18	51	8	7	18
11	17	19	15	15	16	13	17	10	20	15	19
12	16	15	15	15	14	15	15	9	17	18	13
DS	15	28	13	14	76	10	77	14	14	13	—

Table B–205. South Dakota Site 4 Left, Short Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	12	10	8	6	9	6	10	8	9	6	10
02	6	16	6	6	19	6	19	6	6	8	16
03	8	10	10	6	8	6	9	7	9	6	9
04	9	6	9	10	6	9	6	6	10	9	6
05	5	13	5	3	60	3	62	4	5	4	30
06	8	6	7	9	5	10	5	7	8	10	4
08	5	13	5	3	62	3	67	4	5	4	34
10	5	7	5	4	7	4	8	23	6	4	9
11	8	10	8	6	8	6	8	9	10	6	14
12	9	8	9	10	6	10	6	6	10	13	6
DS	5	16	5	6	44	4	49	5	8	6	—

Table B–206. South Dakota Site 4 Right, IRI Filter.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	36	32	32	17	30	34
05	28	91	91	29	29	73
08	29	91	91	29	29	73
10	16	31	31	61	13	41
11	27	33	33	14	30	31
DS	30	79	80	38	27	—

Table B–207. South Dakota Site 4 Right, Long Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	89	68	70	77	57	83
05	68	98	97	52	78	64
08	70	97	99	52	76	63
10	77	52	51	87	46	86
11	57	78	76	47	78	54
DS	82	64	63	86	53	—

Table B–208. South Dakota Site 4 Right, Medium Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	26	26	26	9	23	26
05	20	87	88	17	22	66
08	20	88	88	16	22	67
10	7	20	19	51	8	28
11	20	28	28	10	22	26
DS	20	72	74	23	20	—

Table B–209. South Dakota Site 4 Right, Short Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	15	13	13	7	11	12
05	8	71	69	5	8	28
08	8	69	72	5	9	29
10	4	10	10	28	5	9
11	7	15	15	8	11	10
DS	7	26	28	4	7	—

Table B–210. South Dakota Site 5 Left, IRI Filter.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	76	68	66	51	80	63	75	29	63	64	77
02	70	69	64	51	73	61	70	24	62	65	72
03	71	68	73	61	75	72	78	27	72	76	73
04	57	51	65	58	56	64	65	25	67	68	54
05	76	68	68	51	92	63	85	29	64	65	74
06	69	61	72	64	68	83	77	41	81	79	62
08	79	72	76	61	85	73	**95**	30	73	77	77
10	32	27	28	25	31	40	32	77	39	30	26
11	68	67	71	61	68	78	78	38	84	78	66
12	70	65	76	68	70	79	82	30	78	84	69
DS	74	72	67	54	78	62	75	24	61	69	—

Table B–211. South Dakota Site 5 Left, Long Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	91	81	80	83	81	87	87	76	70	86	88
02	80	93	91	80	92	82	85	63	65	84	75
03	79	92	95	83	93	84	88	60	66	88	74
04	84	80	85	88	82	90	90	65	71	91	80
05	80	92	93	81	99	83	91	63	65	85	74
06	87	82	85	90	84	94	92	72	75	93	83
08	86	86	89	89	91	90	98	66	71	94	80
10	76	63	61	65	63	72	67	86	60	66	73
11	71	66	67	72	66	76	72	61	83	74	66
12	86	84	89	91	86	93	94	66	73	96	83
DS	88	75	74	80	75	83	81	72	65	83	—

Table B–212. South Dakota Site 5 Left, Medium Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	73	61	61	44	74	58	73	26	61	59	74
02	67	64	61	46	68	57	70	24	62	61	66
03	69	66	71	54	72	67	78	28	72	73	71
04	52	46	62	52	51	58	59	25	64	62	48
05	73	61	63	45	86	58	84	27	62	61	73
06	65	57	70	57	64	79	73	40	80	75	57
08	78	68	72	54	84	67	95	29	72	72	77
10	30	27	30	24	30	39	33	72	41	31	26
11	68	67	71	55	68	74	79	38	84	74	66
12	67	62	74	62	67	75	78	31	79	82	65
DS	70	66	62	48	71	57	74	23	60	65	—

Table B–213. South Dakota Site 5 Left, Short Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	38	15	29	9	20	18	32	4	32	19	27
02	27	25	31	13	19	16	26	5	30	23	21
03	32	19	40	11	19	19	35	4	34	22	31
04	18	13	24	11	14	11	17	6	20	16	13
05	37	17	33	10	38	18	36	5	32	23	28
06	29	16	28	12	16	28	25	5	36	18	12
08	33	18	33	13	36	19	66	4	34	27	39
10	9	8	9	7	9	9	8	19	9	8	6
11	24	14	24	8	12	17	22	3	40	17	24
12	28	23	31	16	20	18	37	4	34	30	30
DS	22	21	24	13	14	12	32	3	26	30	—

Table B–214. South Dakota Site 5 Right, IRI Filter.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	81	83	85	30	73	82
05	75	**96**	85	29	71	80
08	84	85	**96**	27	81	86
10	29	31	26	86	31	21
11	79	78	87	33	83	75
DS	75	87	85	21	68	—

Table B–215. South Dakota Site 5 Right, Long Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	92	84	88	65	70	83
05	82	99	93	64	77	82
08	87	93	98	60	81	79
10	65	64	60	78	54	67
11	69	78	81	54	82	65
DS	82	83	79	67	64	—

Table B–216. South Dakota Site 5 Right, Medium Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	79	84	82	32	71	81
05	74	95	85	29	70	80
08	83	85	94	29	80	85
10	30	32	28	84	33	23
11	79	78	86	36	83	75
DS	73	88	83	22	67	—

Table B–217. South Dakota Site 5 Right, Short Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	49	38	42	6	41	38
05	37	54	64	5	43	43
08	39	64	73	6	46	48
10	10	8	10	35	12	11
11	28	26	29	5	42	26
DS	31	37	48	6	35	—

Table B–218. South Dakota Site 6 Left, IRI Filter.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	82	67	66	68	73	70	74	58	68	67	74
02	64	64	69	64	72	67	72	51	66	62	70
03	63	64	82	71	82	73	81	55	66	65	81
04	65	65	75	71	80	72	81	55	66	66	75
05	70	69	85	78	**95**	80	**95**	61	71	70	86
06	66	67	78	72	82	79	81	62	70	70	80
08	71	70	83	79	**95**	80	**95**	62	71	70	84
10	56	50	58	56	62	63	63	86	55	60	66
11	64	65	70	68	74	74	75	56	77	64	72
12	64	62	69	65	70	70	70	58	61	81	82
DS	70	70	82	75	84	80	83	63	68	82	—

Table B–219. South Dakota Site 6 Left, Long Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	98	74	71	77	85	77	86	73	72	59	79
02	73	96	95	93	83	93	81	72	78	67	87
03	71	95	96	92	83	92	82	68	78	62	83
04	76	93	93	96	88	96	86	73	81	62	89
05	85	83	83	88	99	87	98	69	84	51	80
06	77	93	92	96	87	97	85	76	82	64	90
08	86	81	82	86	98	85	99	68	82	50	79
10	73	73	68	74	69	77	67	95	64	74	90
11	72	79	78	82	83	83	81	63	93	53	75
12	58	66	61	61	51	64	49	73	53	97	77
DS	79	87	83	89	80	90	78	89	75	78	—

Table B–220. South Dakota Site 6 Left, Medium Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	69	56	68	63	67	66	68	49	66	70	71
02	59	50	58	49	54	51	55	37	58	53	54
03	60	49	74	61	79	63	79	46	63	65	79
04	59	50	68	59	68	58	68	43	60	61	63
05	60	50	74	62	91	63	90	47	62	66	83
06	59	51	68	58	69	66	69	48	65	63	65
08	62	50	74	63	90	64	89	48	63	67	82
10	47	35	50	43	51	50	51	78	49	45	49
11	59	50	69	58	69	65	69	48	67	65	72
12	62	53	70	61	71	63	71	43	63	71	73
DS	63	54	73	62	83	65	82	46	64	73	—

Table B–221. South Dakota Site 6 Left, Short Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	27	9	28	10	20	12	21	6	25	15	27
02	18	13	15	9	9	10	10	7	17	13	12
03	16	6	32	9	18	8	22	4	19	10	30
04	16	9	22	14	17	12	16	6	18	14	13
05	16	7	27	13	42	10	43	4	18	13	31
06	18	10	20	11	13	19	12	6	23	12	11
08	18	8	26	12	43	10	46	4	19	13	28
10	10	5	12	7	7	7	6	26	13	9	9
11	16	7	23	8	13	10	15	4	25	10	26
12	20	12	25	14	17	12	16	7	21	24	19
DS	17	12	26	12	20	11	24	4	20	19	—

Table B–222. South Dakota Site 6 Right, IRI Filter.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	81	73	75	53	60	72
05	71	**96**	**96**	62	80	90
08	72	**96**	**97**	61	80	89
10	52	61	60	90	51	69
11	57	81	81	53	80	74
DS	69	88	88	70	71	—

Table B–223. South Dakota Site 6 Right, Long Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	98	82	85	64	63	79
05	82	99	96	65	79	86
08	85	96	99	62	76	83
10	64	65	62	91	62	83
11	63	79	76	62	91	75
DS	79	86	83	84	76	—

Table B–224. South Dakota Site 6 Right, Medium Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	63	73	72	46	63	68
05	66	92	91	58	71	86
08	65	91	93	58	70	89
10	42	56	57	83	49	58
11	57	78	77	52	71	70
DS	60	82	85	55	63	—

Table B–225. South Dakota Site 6 Right, Short Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	27	32	33	6	23	17
05	21	54	54	4	26	22
08	21	54	54	4	24	21
10	6	8	8	30	9	7
11	13	22	23	5	24	13
DS	15	34	38	6	20	—

Table B–226. South Dakota Site 7 Left, IRI Filter.

Correlation	Correlated Device										
Reference	01	02	03	04	05	06	08	10	11	12	DS
01	80	71	66	60	75	65	74	27	65	63	85
02	73	72	68	66	70	68	75	26	69	69	79
03	73	73	77	74	70	75	79	25	76	78	79
04	66	66	74	75	63	74	75	25	76	79	68
05	71	68	64	59	76	62	78	23	62	63	78
06	71	68	75	74	65	84	78	32	81	79	68
08	79	75	76	71	78	75	**96**	26	75	75	80
10	30	28	25	24	25	30	28	82	32	25	25
11	71	73	75	72	67	79	81	32	82	77	74
12	69	69	77	79	66	79	79	26	81	83	72
DS	82	79	71	68	81	68	80	23	68	72	—

Table B–227. South Dakota Site 7 Left, Long Wavelengths.

Correlation	Correlated Device										
Reference	01	02	03	04	05	06	08	10	11	12	DS
01	93	77	78	82	84	84	87	75	72	84	91
02	76	97	91	87	86	87	82	60	69	87	81
03	77	93	95	91	90	91	86	61	72	91	82
04	81	87	92	93	91	93	88	63	73	94	87
05	83	87	90	91	95	92	92	64	74	92	86
06	83	87	92	93	93	95	89	67	75	95	88
08	87	82	87	89	92	90	97	68	79	91	84
10	76	60	62	63	64	67	68	88	62	64	73
11	74	70	74	74	75	76	80	63	87	78	70
12	83	87	93	94	93	95	90	64	76	97	89
DS	90	81	83	87	86	88	84	73	68	89	—

Table B–228. South Dakota Site 7 Left, Medium Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	76	64	62	53	72	59	72	24	63	58	80
02	72	69	67	61	67	65	74	24	68	66	74
03	71	71	76	68	67	72	79	26	76	74	77
04	61	61	73	70	57	69	69	24	75	75	62
05	68	62	60	53	73	57	77	20	60	58	75
06	67	65	74	69	61	80	74	34	80	75	64
08	77	73	72	64	77	69	95	23	72	70	81
10	28	26	26	22	22	31	26	79	32	24	25
11	70	73	75	66	65	75	80	32	80	74	75
12	65	66	77	75	62	75	75	26	80	80	69
DS	79	74	68	62	79	64	79	22	68	69	—

Table B–229. South Dakota Site 7 Left, Short Wavelengths.

Correlation Reference	Correlated Device										
	01	02	03	04	05	06	08	10	11	12	DS
01	43	21	33	14	31	22	34	4	35	24	42
02	34	32	37	23	31	24	37	5	37	31	35
03	35	24	47	17	32	20	36	3	39	26	47
04	28	23	34	20	24	18	29	5	30	25	24
05	30	27	30	19	46	22	58	3	32	29	51
06	35	24	32	18	25	34	30	4	38	23	22
08	34	33	36	23	58	27	75	3	41	35	59
10	10	8	8	7	6	7	7	36	9	8	4
11	29	19	30	13	25	20	28	3	37	21	34
12	35	31	38	25	34	23	39	4	39	37	40
DS	32	35	37	24	37	22	42	3	34	40	—

Table B–230. South Dakota Site 7 Right, IRI Filter.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	85	88	89	35	76	87
05	81	**96**	93	35	76	90
08	85	93	**97**	32	81	91
10	32	32	30	89	30	31
11	82	83	87	32	85	82
DS	82	95	91	33	76	—

Table B–231. South Dakota Site 7 Right, Long Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	95	86	88	69	71	88
05	85	99	97	57	82	86
08	87	97	98	56	82	83
10	69	57	56	81	51	72
11	70	82	82	51	86	71
DS	87	86	83	72	70	—

Table B–232. South Dakota Site 7 Right, Medium Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	83	88	87	38	73	86
05	80	95	93	36	74	89
08	83	93	96	35	78	89
10	33	34	33	88	34	33
11	81	82	85	37	84	81
DS	80	94	91	36	73	—

Table B–233. South Dakota Site 7 Right, Short Wavelengths.

Correlation Reference	Correlated Device					
	01	05	08	10	11	DS
01	52	36	46	7	41	46
05	41	60	62	6	44	56
08	43	62	77	6	47	45
10	12	10	12	50	17	16
11	30	25	31	6	43	33
DS	39	52	62	8	44	—

Table B–234. South Dakota Site 8 Left, IRI Filter.

Correlation Reference	Correlated Device									
	01	02	03	04	05	06	08	11	12	DS
01	85	57	71	73	77	73	74	70	75	77
02	62	49	54	50	54	51	52	59	53	52
03	67	48	79	74	83	72	82	68	75	82
04	69	50	78	77	85	72	83	68	77	77
05	73	51	84	82	**96**	77	**95**	72	81	86
06	69	51	75	72	79	77	77	69	74	77
08	70	50	82	79	**95**	74	**97**	70	78	86
11	67	52	72	71	76	72	74	80	75	72
12	71	52	78	77	84	74	81	72	80	81
DS	73	52	81	77	85	77	84	68	81	—

Table B–235. South Dakota Site 8 Left, Long Wavelengths.

Correlation Reference	Correlated Device									
	01	02	03	04	05	06	08	11	12	DS
01	97	75	73	76	85	78	85	78	77	81
02	75	93	93	91	84	93	81	68	93	87
03	72	92	94	92	83	91	80	67	93	85
04	75	91	92	92	84	92	82	65	93	86
05	85	84	83	84	99	86	98	76	86	78
06	78	93	92	92	86	95	83	69	94	89
08	85	81	80	82	98	83	99	77	83	76
11	79	68	67	66	77	70	77	88	69	66
12	77	93	93	93	86	94	83	69	95	89
DS	81	87	85	86	78	89	76	65	89	—

Table B–236. South Dakota Site 8 Left, Medium Wavelengths.

Correlation Reference	Correlated Device									
	01	02	03	04	05	06	08	11	12	DS
01	73	35	71	64	77	64	73	66	67	73
02	43	32	41	34	38	34	36	43	36	34
03	65	33	70	63	77	59	76	64	64	77
04	64	34	69	66	75	58	71	64	66	63
05	67	33	73	67	92	61	90	64	67	79
06	63	34	64	58	68	66	64	64	61	59
08	63	32	69	64	90	58	94	60	64	80
11	63	35	67	60	71	62	68	68	64	72
12	67	36	70	66	74	61	71	68	70	67
DS	64	34	67	63	75	59	76	64	67	—

Table B–237. South Dakota Site 8 Left, Short Wavelengths.

Correlation Reference	Correlated Device									
	01	02	03	04	05	06	08	11	12	DS
01	42	6	35	19	38	18	40	31	21	38
02	13	9	12	8	11	6	11	12	9	6
03	27	5	40	17	32	13	35	28	18	36
04	28	8	33	28	38	15	40	28	29	25
05	36	7	42	27	68	21	71	34	27	51
06	25	6	24	15	26	24	28	22	16	12
08	36	7	41	28	71	21	79	34	28	52
11	21	5	25	13	23	10	25	26	15	31
12	30	9	34	29	38	16	41	30	32	26
DS	24	6	30	25	32	12	35	30	26	—

Table B–238. South Dakota Site 8 Right, IRI Filter.

Correlation Reference	Correlated Device				
	01	05	08	11	DS
01	82	75	81	64	79
05	71	**95**	91	77	88
08	76	91	**96**	78	91
11	60	75	75	76	75
DS	74	88	90	77	—

Table B–239. South Dakota Site 8 Right, Long Wavelengths.

Correlation Reference	Correlated Device				
	01	05	08	11	DS
01	98	82	85	52	84
05	81	99	96	69	86
08	85	96	99	66	83
11	51	69	66	81	57
DS	83	85	83	57	—

Table B–240. South Dakota Site 8 Right, Medium Wavelengths.

Correlation Reference	Correlated Device				
	01	05	08	11	DS
01	72	76	82	70	78
05	69	93	87	75	85
08	72	87	93	76	88
11	62	70	78	72	74
DS	69	79	88	74	—

Table B–241. South Dakota Site 8 Right, Short Wavelengths.

Correlation Reference	Correlated Device				
	01	05	08	11	DS
01	39	33	41	31	35
05	39	76	60	39	54
08	33	60	70	34	44
11	21	22	26	29	24
DS	30	39	47	33	—

Appendix C: Interpretation of 1993 RPUG Cross Correlation Results

This appendix interprets the cross correlation results from the 1993 RPUG study. These analyses establish a relationship between cross correlation level and scatter, RMS error, and individual error in summary IRI measurement. First, overall results for repeatability in IRI measurement (listed in Appendix A) are compared to the appropriate cross correlation values (listed in Appendix B). Second, RMS difference in IRI measurement compared to the Dipstick (listed in Appendix A) is compared to cross correlation of profile with Dipstick measurements (listed in Appendix B). Third, all possible pairs of measurement from the 1993 RPUG study are examined. In this case, every possible IRI comparison (all measurement on a given site compared to all others) are compared to every possible cross correlation value between the corresponding pairs of profiles. This covers 378,758 paired measurements. The analyses are repeated with profiles from devices with ultrasonic sensors eliminated, since they are no longer in use.

REPEATABILITY

In Appendix A, a composite level of repeatability was calculated for each of 33 inertial profilers from the 1993 RPUG study. Each individual measured IRI value was compared to the average by a given device on a given site and wheeltrack. Often, 10 measurements were made on both wheeltracks of 8 sites. Thus, the 10 individual IRI values for a given wheeltrack were compared to their average. This was repeated for each site (and wheeltrack), and all of the values (usually 160) of percent difference from the average were assembled into a distribution for that device. (See figure A–1.) The standard deviation exhibited by each device is listed in tables C–1 and C–2. These values quantify the scatter in IRI measurement, and represent an overall assessment of repeatability.

The tables also list the average cross correlation values for each device when all of its measurements of a given wheeltrack are compared to each other. In this case, the IRI filter was used in the procedure. These values are the average of all cross correlation values for all possible combinations of repeat measurements (i.e., repeat 1 to repeat 2, repeat 1 to repeat 3, etc.). When 10 repeat measurements were made, the corresponding value in the table represents 45 comparisons. Table C–1 lists the results for the left wheeltrack and table C–2 lists the results for the right. (Not every device measured both wheeltracks, and some devices did not measure some of the sites at all.)

Overall, a vague relationship exists between the ratings of "scatter" and the cross correlation values. The lowest level of scatter (1.63 percent) in table C–1 is exhibited by device S08, and is accompanied by cross correlation values for all 8 sites greater than 0.90. The highest level of scatter (10.60 percent) is exhibited by device S03, which shows some of the lowest cross correlation values. An important observation to be made about the cross correlation values is that they depend on the test site as well as the device. Several of the profilers have high cross correlation levels on some sites and low levels on others. This is because some sites are more problematic to some profilers than others. Since the listed standard deviation values often pertain to both wheeltracks of all sites, a direct comparison to cross correlation level is not possible.

Table C–1. Repeatability of profilers in measurement of IRI, left side.

Region	Device	Sensor Type	Std. Dev. (%)	Average Correlation at Each Site							
				1	2	3	4	5	6	7	8
M	M01	U	4.77	.78	.71	.52	.53	.87	.81	.80	.57
	M02	U	4.74	.81	.49	.44	.60	.82	.74	.82	.55
	M03	L	3.59	.79	.71	.78	.74	**.94**	.86	—	.87
	M05	U	7.80	.61	.62	.47	.57	.87	.46	.65	.50
	M06	O	1.92	.88	.92	.82	.90	**.97**	**.94**	**.98**	.93
N	N03	U	6.65	.68	.37	.66	.60	.45	.28	—	—
	N04	U	6.63	.51	.21	.65	.80	.56	.48	—	—
	N06	U	5.64	.78	.48	.36	.60	.61	.41	—	—
	N07	L	4.15	.92	.91	.77	.87	.81	.82	—	—
	N08	O	3.59	**.94**	.89	.81	.86	.93	.87	—	—
	N09	O	3.49	.91	.80	.85	.84	.89	.80	—	—
P	P01	L	2.72	**.96**	.92	.91	**.96**	**.95**	**.94**	**.94**	.93
	P02	U	3.76	.90	.59	.48	.61	.83	.86	.84	.73
	P03	U	3.87	.89	.49	.46	.63	.82	.89	.89	.83
	P04	L	3.80	**.96**	.71	.87	.86	.91	**.95**	.91	.81
	P05	O	1.86	.92	.87	**.96**	**.97**	**.95**	**.96**	**.95**	**.96**
	P06	U	7.46	.90	.49	.25	.52	.86	.75	.60	.74
	P07	O	2.57	.93	.82	.91	.93	**.97**	**.96**	.87	.60
	P08	L	2.37	.88	.73	.92	.93	.92	**.95**	.92	.88
	P73	U	3.84	.92	.61	.47	.55	.86	.86	.82	.77
	P74	U	3.00	.92	.79	.52	.67	.87	.89	.84	.77
	P75	U	3.20	.90	.69	.49	.63	.85	.85	.81	.76
	P76	U	2.28	.91	.81	.51	.69	.87	.88	.80	.73
S	S01	U	3.57	.81	.30	.42	.30	.76	.82	.80	.85
	S02	U	7.62	.83	.49	.64	.36	.69	.64	.72	.49
	S03	U	10.60	.70	.16	.29	.20	.73	.82	.77	.79
	S04	U	5.65	.67	.25	.29	.23	.58	.71	.75	.77
	S05	O	5.47	**.94**	.91	.91	.89	.92	**.95**	.76	**.96**
	S06	U	4.78	.73	.23	.28	.20	.83	.79	.84	.77
	S08	O	1.63	**.95**	.93	**.95**	.92	**.95**	**.95**	**.96**	**.97**
	S10	L	2.49	.90	.71	.73	.62	.77	.86	.82	—
	S11	U	5.09	.70	.21	.32	.29	.84	.77	.82	.80
	S12	U	7.46	.71	.19	.28	.23	.84	.81	.83	.80

M - Mississippi N - Nevada P - Pennsylvania S - South Dakota
O - Optical U - Ultrasonic L - Laser

Table C–2. Repeatability of profilers in measurement of IRI, right side.

Region	Device	Sensor Type	Std. Dev. (%)	Average Correlation at Each Site							
				1	2	3	4	5	6	7	8
M	M02	U	4.74	.80	.55	.55	.66	.84	.77	.79	.57
	M03	L	3.59	.90	.90	.76	.84	**97**	.92	—	.93
	M05	U	7.80	.75	.68	.39	.47	.89	.60	.59	.57
	M06	O	1.92	**.95**	**.94**	.89	**.95**	**.97**	**.98**	**.98**	**.97**
N	N03	U	6.65	.77	.49	.55	.59	.53	.43	—	—
	N04	U	6.63	.56	.30	.40	.77	.64	.63	—	—
	N06	U	5.64	.81	.45	.34	.62	.69	.56	—	—
	N07	L	4.15	.93	.93	.90	.88	.83	.86	—	—
	N08	O	3.59	.92	.91	.91	.84	.93	.87	—	—
	N09	O	3.49	.90	**.95**	**.94**	.84	.91	.89	—	—
P	P01	L	2.72	**.94**	.88	.88	**.97**	**.97**	**.95**	.91	.88
	P02	U	3.76	.88	.67	.53	.73	.86	.88	.85	.70
	P03	U	3.87	.89	.45	.58	.62	.79	.85	.86	.71
	P04	L	3.80	**.95**	.60	.84	.83	.88	.79	.91	.78
	P05	O	1.86	**.95**	.86	**.94**	**.96**	**.96**	**.96**	**.96**	.93
	P06	U	7.46	.89	.49	.48	.79	.88	.89	.85	.79
	P07	O	2.57	**.96**	.83	.92	**.94**	**.98**	**.98**	**.94**	**.94**
	P08	L	2.37	.92	.88	.91	**.95**	**.95**	**.96**	**.95**	.88
	P73	U	3.84	.92	.62	.53	.62	.89	.88	.83	.74
	P74	U	3.00	.91	.75	.59	.66	.82	.90	.84	.70
	P75	U	3.20	.90	.70	.52	.79	.88	.87	.81	.71
	P76	U	2.28	.92	.81	.48	.83	.89	.89	.86	.71
S	S01	U	3.57	.83	.47	.45	.36	.81	.81	.85	.82
	S05	O	5.47	**.95**	**.94**	.92	.91	**.96**	**.96**	**.96**	**.95**
	S08	O	1.63	**.95**	.93	**.96**	.91	**.96**	**.97**	**.97**	**.96**
	S10	L	2.49	.88	.84	.80	.61	.86	.90	.89	—
	S11	U	5.09	.70	.41	.33	.30	.83	.80	.85	.76

M - Mississippi N - Nevada P - Pennsylvania S - South Dakota
O - Optical U - Ultrasonic L - Laser

To remedy this, a standard deviation value was calculated to correspond to each value for cross correlation in tables C–1 and C–2. Thus, new values of standard deviation were calculated that only include the error in measurement of IRI on one wheeltrack of one site by one device. Usually, this is the standard deviation of 10 values, representing 10 repeat measurements. When this is done, all 452 cross correlation values in the tables can be paired to a level of scatter in IRI for the appropriate combination of device and wheeltrack.

Figure C–1 compares these values. When the cross correlation level is near 1, the scatter in IRI (standard deviation) is near zero. This is because a cross correlation level of 1 indicates total agreement in the components of profile that affect the IRI. As the cross correlation level decreases, the largest observed scatter in IRI measurement increases. This is because the profiles themselves do not agree as well. In addition, when cross correlation decreases too far the potential for agreement in IRI caused by compensating error increases, so the range of RMS error values spans a range from zero to some large value.

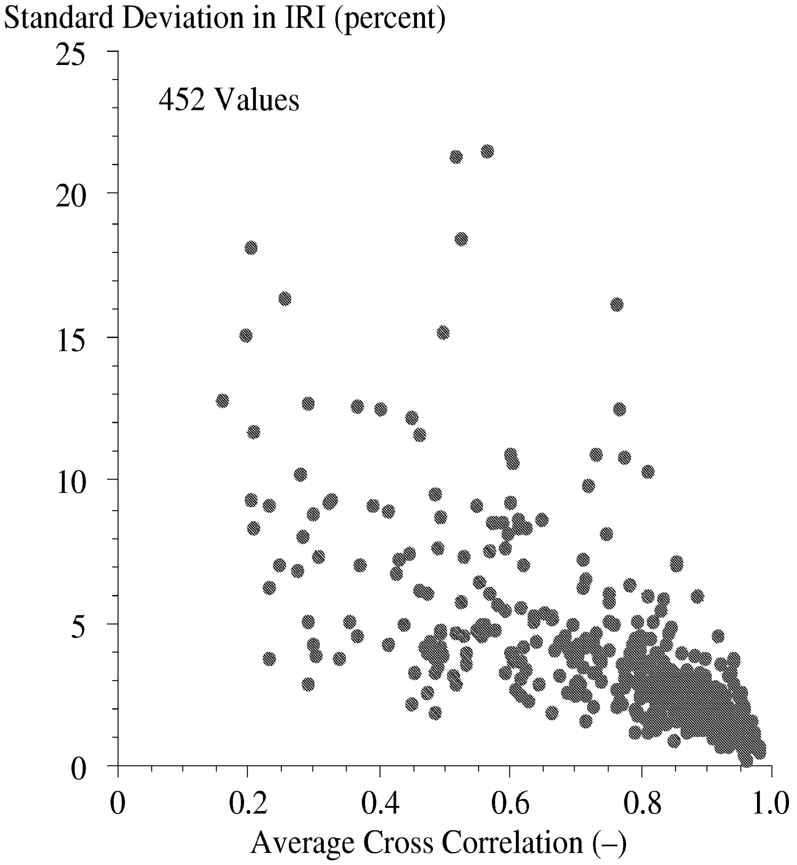

Figure C–1. Comparison of IRI scatter and cross correlation.

The values that occupy the lower left side of figure C-1 represent cases where the profiles did not agree very well, but consistent IRI values were observed. For example, device P76 measured the left wheeltrack of site 3 with an average cross correlation level of 0.51, but the 10 measurements only had a standard deviation of 3.2 percent of their average. The output of the IRI filter for part of three of the measurements are shown in figure C–2. Even though the overall IRI values are very close, the profiles agree very poorly. These profiles could certainly not be used to study the distribution of roughness within the site. Much of the apparent roughness in these profiles is noise. The agreement in IRI is simply due to the fact that the same amount of noise appears in each measurement. The low cross correlation value casts doubt on the accuracy of the IRI values, even though they are similar. The low correlation value may also indicate that this profiler can not be relied upon to produce repeatable IRI values on other sites of similar roughness content and surface texture.

In contrast, device P01 measured the left wheeltrack of site 3 with an average cross correlation level of 0.91, and the 10 measurements had a standard deviation of 2.8 percent of their average. In this case the high level of repeatability in IRI measurement is a direct consequence of good repeatability in profile measurement. The output of the IRI filter for part of three of these measurements are shown in figure C–3. These three traces are very similar, and show high levels of IRI content of approximately the same magnitude and in the same locations. The high average cross correlation value of these measurements indicates that this profiler can be expected to produce repeatable IRI values on other sites of similar roughness content and surface texture.

The 10 measurements by device P01 were an average of 2.7 percent higher than the Dipstick measurement of the same site, but the 10 measurements by device P76 were an average of 53.0 percent higher than the Dipstick. Thus, even though device P76 produced overall IRI values that were repeatable, they exhibited a large upward bias.In this case, poor repeatability of filtered profile served as a warning of poor accuracy in the summary index values.

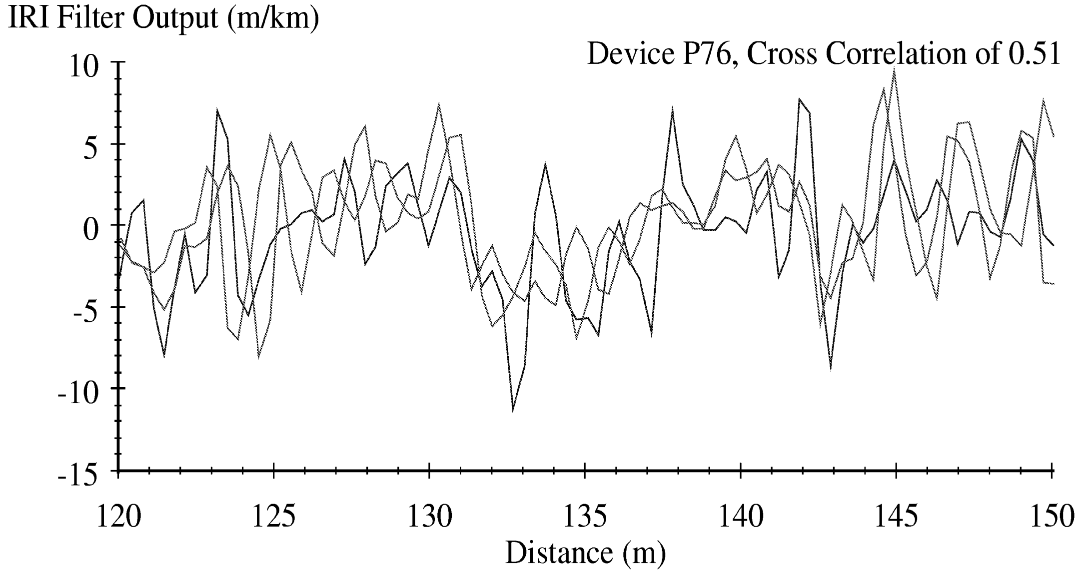

Figure C-2. Poorly-correlated IRI filter output.

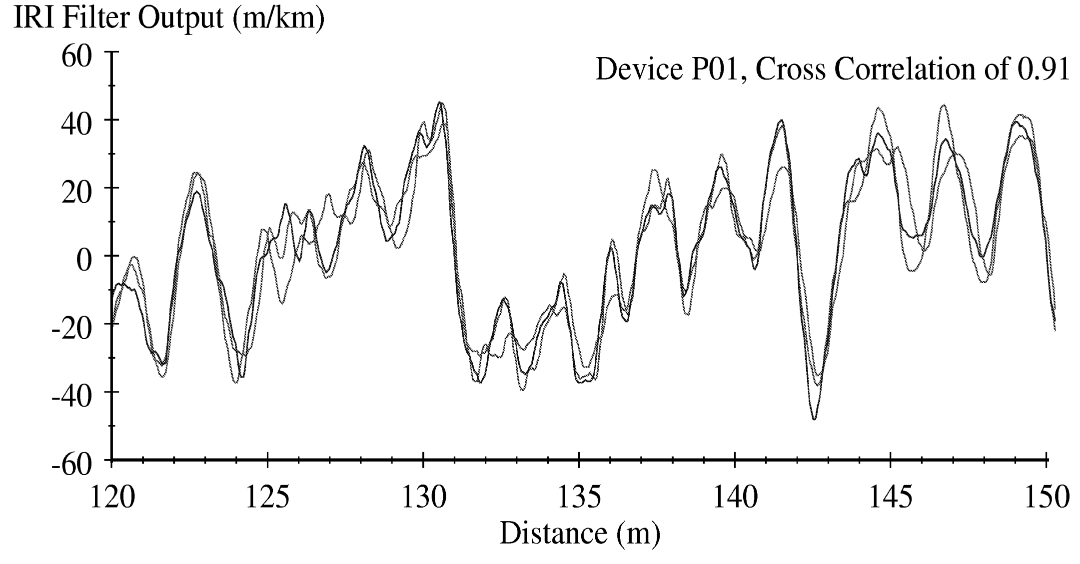

Figure C-3. Well-correlated IRI filter output.

AGREEMENT TO DIPSTICK

In Appendix A, composite levels of agreement to the Dipstick in IRI measurement were calculated for each of 33 inertial profilers from the 1993 RPUG study. Each individual measured IRI value was compared to the corresponding Dipstick value. Most devices made 10 measurements on both wheeltracks of 8 sites. Thus, the 10 individual IRI values for a given wheeltrack were compared to the appropriate Dipstick value. This was repeated for each site (and wheeltrack), and all of the values (usually 160) of percent difference from the Dipstick were assembled into a distribution for that device. (See figure A–2.) The root-mean-square (RMS) "error" exhibited by each device is listed in tables C–3 and C–4.[3] These values quantify a combination of bias and scatter in the IRI values. Bias was also calculated as an indicator of agreement to the Dipstick. This was the average percent difference between each IRI value and the appropriate Dipstick measurement. (Appendix A describes the compilation of these values in detail.)

The tables also list the average cross correlation values for each device when all of their measurements of a given wheeltrack were compared to the Dipstick profile. In this case, the IRI filter was used in the procedure. These values are the average of all cross correlation values for all repeat measurements. When 10 repeat measurements were made, the corresponding value in the table represents the average of 10 cross correlation values. Table C–3 lists the results for the left wheeltrack and table C–4 lists the results for the right. (Not every device measured both wheeltracks, and some devices did not measure some of the sites at all.)

Overall, a vague relationship exists between the ratings of agreement and the cross correlation values. The lowest level of RMS error (5.1 percent) in table C–3 is exhibited by device N09, and is accompanied by cross correlation values for the 12 wheeltracks range from 0.79 to 0.95. The highest level of RMS error (71.7 percent) is exhibited by device S06, and is accompanied by some of the lowest cross correlation values. Note that device N08 exhibits a low level of bias, but a high RMS error, and the cross correlation values are somewhat poor.

An important observation to be made about the cross correlation values is that they depend on the test site as well as the device. Several of the profilers have high cross correlation levels on some sites and low levels on others. This is because some sites are more problematic to some profilers than others. Since the listed standard deviation values often pertain to both wheeltracks of all sites, a direct comparison to cross correlation level is not possible.

To remedy this, an RMS error value and a bias level was calculated to correspond to each value for cross correlation in tables C–3 and C–4. Thus, new values were calculated that only include the error in measurement of IRI on one wheeltrack of one site by one device. Usually, this is the composite of 10 values, representing 10 repeat measurements.

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[3] [3] The term "error" is in quotes because the Dipstick, although it was deemed a reference device at the time, is not guaranteed to provide the true IRI value.

When this is done, all 452 cross correlation values in the tables can be paired to a level of RMS error and bias in IRI for the appropriate combination of device and wheeltrack.

Table C–3. Agreement to Dipstick in measurement of IRI, left.

Region	Device	Sensor Type	Bias (%)	RMS Error (%)	Average Correlation to Dipstick at each Site							
					1	2	3	4	5	6	7	8
M	M01	U	11.4	14.8	.74	.61	.50	.52	.80	.78	.71	.54
	M02	U	21.3	26.9	.65	.33	.33	.45	.58	.49	.60	.41
	M03	L	**5.1**	10.8	.78	.64	.57	.46	.84	.74	—	.80
	M05	U	9.3	15.9	.67	.60	.42	.34	.73	.57	.73	.61
	M06	O	**4.7**	**8.4**	.84	.71	.54	.71	.86	.78	.84	.84
N	N03	U	26.6	33.1	.54	.29	.67	.54	.45	.34	—	—
	N04	U	40.8	56.8	.33	.18	.57	.65	.48	.44	—	—
	N06	U	10.4	20.2	.63	.44	.36	.59	.46	.48	—	—
	N07	L	-10.6	15.1	.58	.64	.38	.51	.36	.54	—	—
	N08	O	**-2.1**	15.2	.73	.60	.41	.65	.65	.72	—	—
	N09	O	**1.5**	**5.1**	.93	.83	.89	.85	.91	.79	—	—
P	P01	L	9.4	12.3	.84	.63	.86	.87	.89	.86	.75	.77
	P02	U	30.1	34.8	.70	.45	.40	.50	.72	.75	.66	.63
	P03	U	27.3	32.3	.69	.42	.39	.48	.73	.75	.70	.68
	P04	L	12.0	16.3	.77	.61	.79	.86	.88	.80	.73	.72
	P05	O	11.0	14.9	.72	.35	.77	.82	.81	.84	.67	.71
	P06	U	32.4	39.0	.72	.46	.28	.52	.73	.69	.59	.65
	P07	O	11.3	13.3	.83	.60	.80	.83	.87	.88	.73	.57
	P08	L	9.5	11.5	.77	.62	.85	.84	.87	.76	.74	.72
	P73	U	25.7	31.7	.76	.58	.37	.47	.77	.77	.69	.68
	P74	U	23.7	27.9	.78	.62	.44	.53	.75	.74	.70	.69
	P75	U	21.1	26.8	.80	.62	.42	.50	.78	.79	.70	.68
	P76	U	22.6	28.3	.77	.62	.43	.53	.75	.76	.70	.66
S	S01	U	44.8	62.3	.75	.20	.34	.24	.74	.70	.82	.73
	S02	U	18.9	29.2	.83	.50	.55	.38	.72	.70	.79	.52
	S03	U	42.4	68.5	.75	.14	.27	.20	.67	.82	.71	.81
	S04	U	51.1	70.4	.70	.21	.22	.19	.54	.75	.68	.77
	S05	O	**-0.3**	**7.6**	.74	.75	.67	.80	.78	.84	.81	.85
	S06	U	50.6	71.7	.68	.19	.19	.16	.62	.80	.68	.77
	S08	O	**2.9**	**7.3**	.75	.76	.70	.81	.75	.83	.80	.84
	S10	L	13.7	19.1	.29	.30	.33	.29	.24	.63	.23	—
	S11	U	36.0	51.0	.62	.19	.29	.20	.61	.68	.68	.68
	S12	U	51.8	77.3	.76	.16	.24	.19	.69	.82	.72	.81

M - Mississippi N - Nevada P - Pennsylvania S - South Dakota
O - Optical U - Ultrasonic L - Laser

Table C–4. Agreement to Dipstick in measurement of IRI, right.

Region	Device	Sensor Type	Bias (%)	RMS Error (%)	Average Correlation to Dipstick at each Site							
					1	2	3	4	5	6	7	8
M	M02	U	21.3	26.9	.58	.47	.30	.46	.52	.60	.61	.47
	M03	L	**5.1**	10.8	.83	.86	.62	.67	.76	.84	—	.81
	M05	U	9.3	15.9	.74	.69	.34	.51	.66	.69	.69	.63
	M06	O	**4.7**	**8.4**	.76	.80	.47	.77	.80	.86	.89	.80
N	N03	U	26.6	33.1	.68	.34	.43	.58	.48	.42	—	—
	N04	U	40.8	56.8	.41	.21	.24	.64	.50	.54	—	—
	N06	U	10.4	20.2	.76	.38	.33	.56	.54	.55	—	—
	N07	L	-10.6	15.1	.76	.59	.51	.58	.47	.64	—	—
	N08	O	**-2.1**	15.2	.87	.75	.68	.79	.60	.70	—	—
	N09	O	**1.5**	**5.1**	.93	**.95**	.92	.87	.93	.90	—	—
P	P01	L	9.4	12.3	.85	.74	.69	.89	.90	.76	.78	.70
	P02	U	30.1	34.8	.71	.43	.33	.59	.72	.68	.72	.57
	P03	U	27.3	32.3	.71	.36	.46	.52	.68	.67	.74	.61
	P04	L	12.0	16.3	.78	.63	.78	.78	.86	.64	.76	.66
	P05	O	11.0	14.9	.78	.71	.77	.86	.81	.72	.83	.75
	P06	U	32.4	39.0	.73	.43	.38	.66	.70	.67	.73	.64
	P07	O	11.3	13.3	.79	.71	.68	.77	.82	.74	.80	.82
	P08	L	9.5	11.5	.83	.74	.73	.92	.87	.71	.81	.76
	P73	U	25.7	31.7	.78	.51	.37	.57	.74	.68	.74	.64
	P74	U	23.7	27.9	.79	.61	.43	.54	.69	.68	.72	.62
	P75	U	21.1	26.8	.83	.61	.42	.68	.76	.70	.74	.62
	P76	U	22.6	28.3	.78	.71	.37	.72	.74	.70	.75	.63
S	S01	U	44.8	62.3	.72	.35	.36	.30	.75	.69	.82	.74
	S05	O	**-0.3**	**7.6**	.82	.86	.81	.79	.87	.88	**.95**	.88
	S08	O	**2.9**	**7.3**	.78	.85	.77	.80	.85	.88	.91	.90
	S10	L	13.7	19.1	.44	.51	.45	.38	.21	.70	.33	—
	S11	U	36.0	51.0	.60	.34	.31	.27	.68	.71	.76	.77

M - Mississippi N - Nevada P - Pennsylvania S - South Dakota
O - Optical U - Ultrasonic L - Laser

Figure C–4 compares the RMS error levels to the level of cross correlation. When the cross correlation level is near 1, the RMS error is near zero. This is because a cross correlation level of 1 indicates total agreement in the components of profile that affect the IRI. As the cross correlation level decreases, the largest observed RMS error in IRI measurement increases. This is because the profiles themselves do not agree as well. In addition, when cross correlation decreases too far the potential for agreement in IRI caused by compensating error increases, so the range of RMS error values spans a range from zero to some large value. In this case, a cross correlation level of 0.90 is required to guarantee an RMS error level below 5 percent.

AGREEMENT BETWEEN ANY PAIR OF MEASUREMENTS

The discussions of repeatability and agreement to the Dipstick above show that there is a relationship between error in overall IRI measurement and the cross correlation level between profiles. Unfortunately, those data are not comprehensive enough to permit the association of a given level of cross correlation with a desired expected error level in IRI.

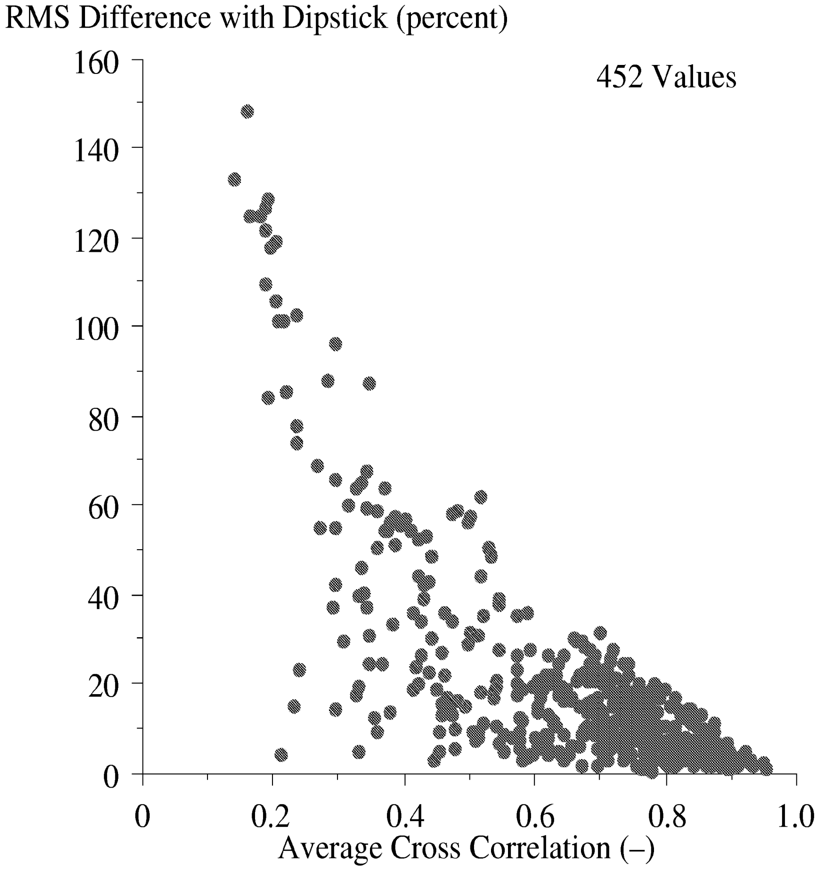

Figure C–4. Comparison of RMS error in IRI and cross correlation.

To help establish this relationship, all possible comparisons of individual measurements from the 1993 RPUG study were examined as individual samples of the relationship. To do this, any pair of profiles that covered the same wheeltrack were cross correlated using IRI filter output. The level of cross correlation was then "paired" with the percent difference in IRI.

The calculation of IRI error and cross correlation level for all possible combinations resulted in 374,758 pairs of values. These pairs include comparisons of Dipstick with inertial profilers, inertial profilers with their own repeat measurements, and comparisons across different inertial profilers. For example, the left wheeltrack of site 4 in Pennsylvania was measured by 12 profilers 10 times each, and once by the Dipstick. (See table B–1.) These 121 measurements permit 14,520 individual comparisons. Note that each pair was compared twice, so that one of the profiles could take the role of reference measurement in each comparison. This was needed because the process does not have reciprocity.

Once the level of IRI error and cross correlation were computed for all pairs, they were assembled into bins by their cross correlation level. Each bin covered a range of 0.01 (out of 1) along the scale. For example, the bin that ranged from 0.93 to 0.94 included 3,394 pairs. The distribution of IRI error level within this bin is shown in figure C–5.

The content of this distribution can be summarized in five ways:

1. **Average**: The average value of IRI error. This should be small, but it will always be greater than zero. (Consider a pair of IRI measurements of 1.00 m/km and 1.05

m/km. They will yield two values of error: 5 percent and -4.76 percent. This non-linearity will cause the average error level to have a non-zero value.)

2. **RMS**: The root mean square error level includes the influence of upward and downward errors. When it is considered in conjunction with the average error level, it would be enough to define the distribution if the Gaussian assumption was reasonable. In figure C–5, this may not be the case.
3. **95th Percentile**: The 95th percentile error level includes the influence of upward and downward errors also. A desired expected 95th percentile error level in IRI should be used to set a minimum cross correlation level between profiles.
4. **Maximum Error**: This is the maximum level of IRI upward bias error observed within the range of cross correlation level under examination. It is simply included to place a bound on the possible error level, and warn users of these results of the inevitable anecdote that a measurement with a high level of cross correlation still showed some disagreement in IRI.
5. **Minimum Error**: This is the maximum level of IRI downward bias error observed within the range of cross correlation level of under examination.

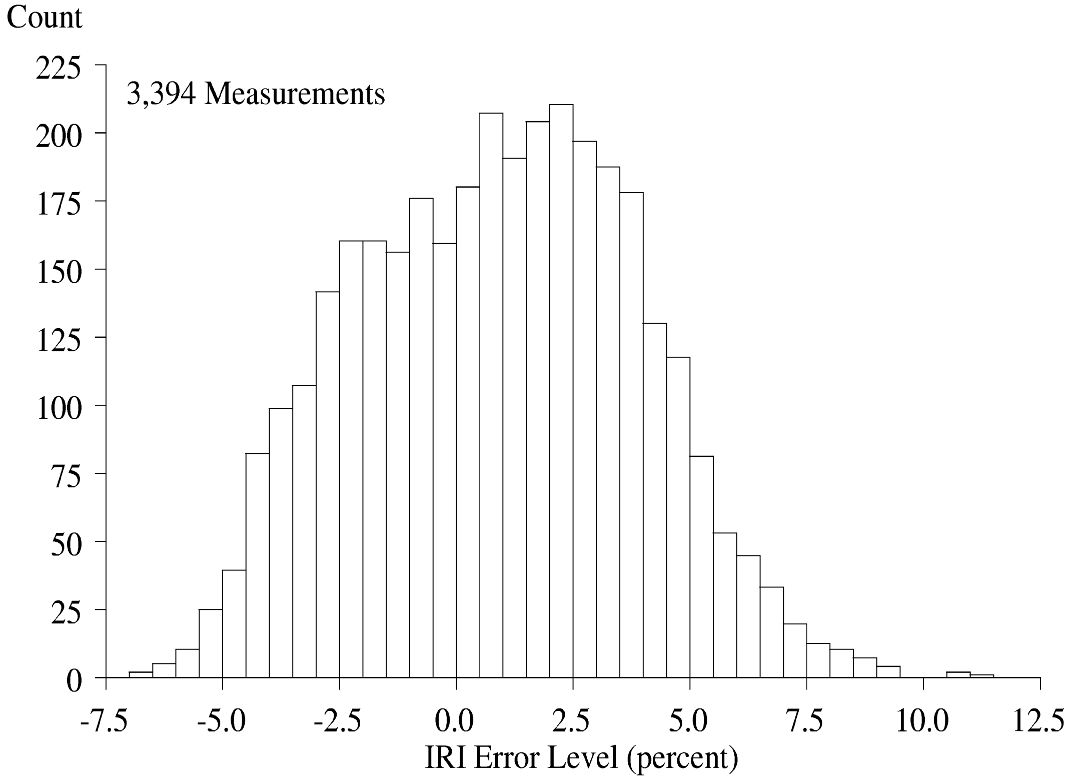

Figure C–5. Distribution of IRI disagreement, cross correlation 0.93-0.94.

These five quantities are displayed in figure C–6 for all 100 possible bins by upper cross correlation limit. The values displayed in figure C–6 are also listed in table C–5, below, so that individual values of interest are easier to read. The table also lists the number of pairs within each bin. The error levels grow quite high when the cross correlation level decreases below about 0.80. The figure is therefore repeated for values of cross correlation above 0.85 in figure C–7.

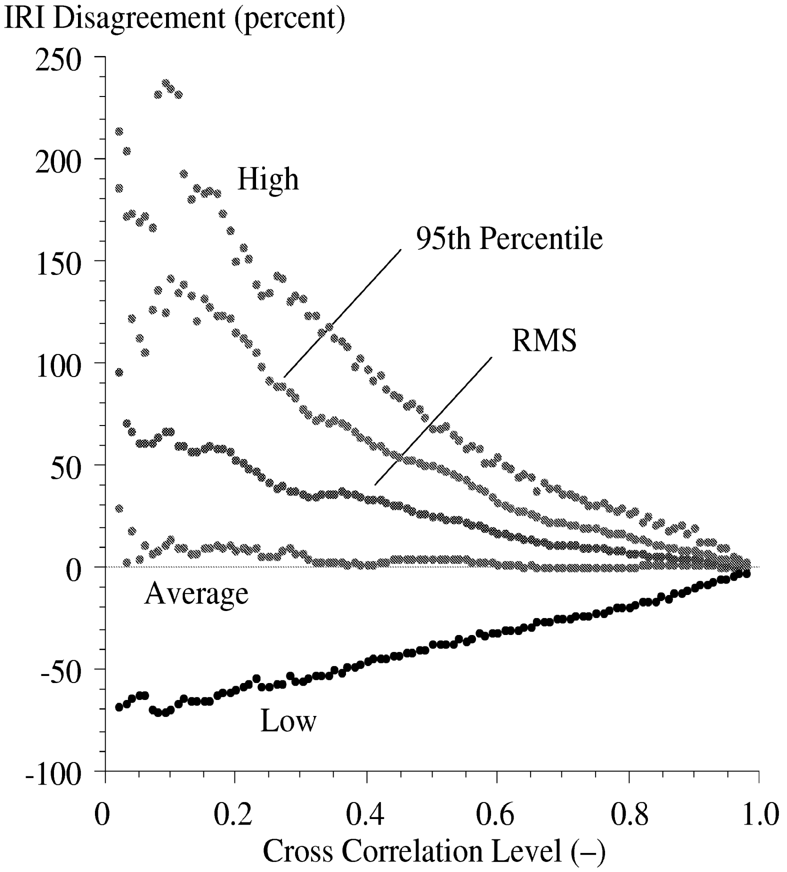

Figure C–6. IRI disagreement at various cross correlation levels.

Road profiling technology has improved significantly since the 1993 RPUG experiment. Unfortunately, the 1993 RPUG data were the only source of repeat measurements by several profilers on the same site at the time this research was done. It is recommended that the same study is performed on data from modern profilers. The use of ultrasonic sensors has been discredited since 1993, in part due to the RPUG experiment. Thus, the analyses described above were repeated without any measurements from profilers with ultrasonic sensors. In this case, only 129,812 pairs were available. Figure C–8 and table C–6 provide the results. In the range of desirable performance, the results did not change significantly.

It is recommended that, until a more relevant data set can be obtained, cross correlation limits are set of various "classes" of profiler based on these values. For example, at a cross correlation level of 0.98, you may expect 95 percent of your IRI measurements to agree within 2 percent. This could be proposed as a threshold limit for a "research class" profiler. At a cross correlation level of 0.94, you may expect 95 percent of your IRI measurements to agree within 5 percent. This could be proposed as a threshold limit for a "project class" profiler. The same limit could be proposed for construction quality control, as long as the test sites were carefully chosen to duplicate the smoothness and texture expected in the field. Lastly, at a cross correlation level of 0.88, you may expect 95 percent of your IRI measurements to agree within 10 percent of each other. This could be proposed as a threshold limit for a "network class" profiler.

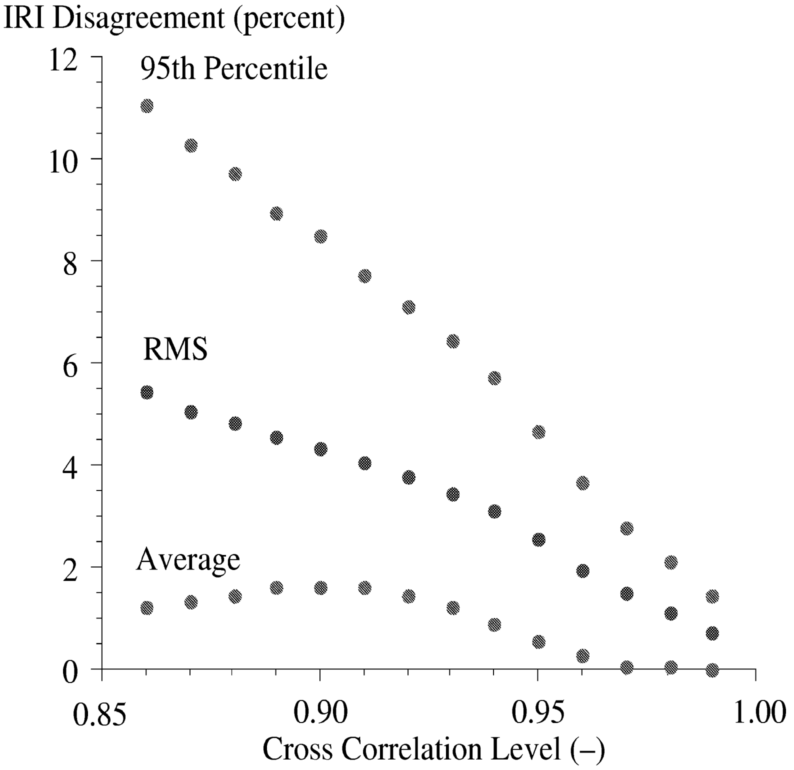

Figure C–7. IRI disagreement at high cross correlation levels.

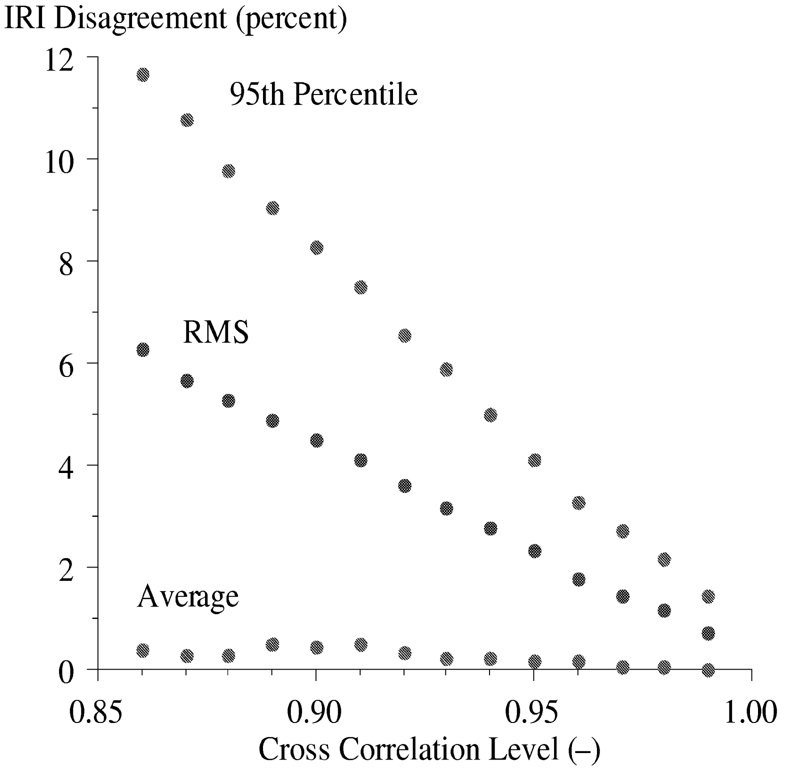

Figure C–8. IRI disagreement associated with cross correlation level, ultrasonic devices excluded.

Table C–5. Expected IRI error associated with cross correlation level.

Cross Correlation Range		Number of Comparisons	Error Level in IRI Measurement (Percent)				
From	To		Average	RMS	95th Percentile	Low	High
.98	.99	877	0.01	0.74	1.47	-2.22	3.39
.97	.98	1543	0.03	1.14	2.14	-3.24	3.65
.96	.97	1956	0.07	1.48	2.76	-4.10	5.20
.95	.96	2393	0.26	1.96	3.65	-5.57	9.47
.94	.95	2902	0.54	2.55	4.69	-5.89	10.16
.93	.94	3394	0.89	3.12	5.74	-6.82	12.43
.92	.93	3704	1.20	3.46	6.45	-7.69	12.49
.91	.92	4677	1.45	3.79	7.09	-8.43	13.03
.90	.91	5753	1.61	4.07	7.73	-10.28	18.76
.89	.90	6707	1.61	4.32	8.49	-10.73	16.95
.88	.89	7522	1.60	4.57	8.96	-12.14	20.56
.87	.88	8369	1.47	4.83	9.71	-12.21	19.38
.86	.87	9051	1.33	5.06	10.29	-14.70	18.69
.85	.86	9380	1.20	5.42	11.06	-14.23	21.81
.84	.85	9768	0.95	5.68	11.52	-16.01	20.30
.83	.84	9941	0.91	6.12	12.49	-16.62	24.70
.82	.83	9718	0.83	6.38	13.26	-16.57	22.12
.81	.82	9695	0.64	6.91	14.19	-17.93	27.35
.80	.81	9450	0.69	7.48	15.61	-19.12	25.94
.79	.80	9179	0.68	7.90	16.18	-18.99	29.13
.78	.79	9046	0.52	8.29	16.73	-19.49	27.88
.77	.78	8572	0.52	8.73	17.27	-21.43	29.13
.76	.77	8146	0.56	9.03	17.88	-22.19	31.30
.75	.76	8147	0.33	9.58	18.85	-22.56	30.23
.74	.75	7609	0.49	10.11	19.58	-23.19	31.13
.73	.74	7352	0.17	10.19	19.88	-23.03	33.78
.72	.73	6986	0.17	10.61	20.77	-23.49	34.64
.71	.72	6675	0.25	10.93	21.17	-24.73	35.47
.70	.71	6350	0.06	11.12	21.79	-25.06	36.00
.69	.70	6092	0.31	11.45	22.45	-25.43	38.64
.68	.69	5869	0.44	11.73	22.72	-25.81	38.44
.67	.68	5588	0.45	12.47	23.99	-26.18	41.36
.66	.67	5207	0.53	12.81	24.49	-26.19	37.88
.65	.66	4989	1.07	13.34	26.15	-28.49	44.84
.64	.65	4835	0.67	14.15	27.42	-29.33	46.13
.63	.64	4493	0.94	14.62	27.87	-30.23	45.14
.62	.63	4313	0.91	15.35	29.11	-30.96	48.25
.61	.62	4273	1.35	16.30	30.81	-30.62	49.46
.60	.61	4245	1.41	17.19	32.43	-32.26	53.58

129,812 comparison are excluded, because their cross correlation level is outside the limits of the table.

Table C–6. Expected IRI error associated with cross correlation level, ultrasonic devices excluded.

Cross Correlation Range		Number of Comparisons	Error Level in IRI Measurement (Percent)				
From	To		Average	RMS	95th Percentile	Low	High
.98	.99	871	0.01	0.74	1.47	-2.22	3.39
.97	.98	1534	0.03	1.14	2.14	-3.24	3.65
.96	.97	1906	0.05	1.47	2.74	-4.10	5.20
.95	.96	2184	0.14	1.79	3.28	-4.59	6.46
.94	.95	2320	0.18	2.31	4.10	-5.72	8.33
.93	.94	2302	0.20	2.78	4.98	-6.82	9.24
.92	.93	2102	0.24	3.15	5.87	-7.69	11.46
.91	.92	2296	0.32	3.63	6.58	-8.43	12.02
.90	.91	2314	0.50	4.12	7.48	-10.28	12.42
.89	.90	2415	0.46	4.48	8.26	-10.73	12.27
.88	.89	2342	0.52	4.90	9.06	-11.04	14.79
.87	.88	2384	0.30	5.30	9.79	-12.15	16.41
.86	.87	2273	0.26	5.67	10.76	-12.49	16.25
.85	.86	2257	0.37	6.28	11.68	-12.76	21.81
.84	.85	2287	0.22	6.60	12.31	-13.98	19.61
.83	.84	2121	0.34	6.90	13.06	-15.51	19.57
.82	.83	1915	0.18	6.82	12.76	-15.83	21.71
.81	.82	1888	-0.10	6.95	13.14	-16.61	19.92
.80	.81	1684	0.09	7.15	13.62	-16.84	21.62
.79	.80	1701	0.16	7.47	14.46	-17.41	22.14
.78	.79	1626	0.38	7.65	14.72	-18.38	22.52
.77	.78	1617	0.38	8.05	15.33	-18.41	22.57
.76	.77	1395	0.53	8.07	15.29	-18.93	23.85
.75	.76	1366	0.12	8.69	16.42	-17.96	22.21
.74	.75	1137	0.29	9.23	17.41	-19.80	27.23
.73	.74	1090	-0.18	9.55	18.01	-21.44	28.10
.72	.73	903	0.25	9.76	17.97	-21.94	28.88
.71	.72	798	0.38	10.74	19.53	-23.42	30.59
.70	.71	740	-0.17	10.08	18.12	-19.96	28.76
.69	.70	745	0.82	11.15	20.00	-22.41	30.38
.68	.69	681	0.65	11.65	20.81	-22.98	29.69
.67	.68	658	0.17	12.16	21.40	-23.30	30.12
.66	.67	597	0.52	12.39	23.13	-23.64	34.68
.65	.66	519	0.65	12.43	22.25	-23.54	32.09
.64	.65	616	0.87	12.83	24.30	-24.97	33.51
.63	.64	600	0.22	12.63	23.52	-30.23	43.33
.62	.63	592	1.60	12.02	23.26	-27.54	38.00
.61	.62	575	0.30	11.66	22.87	-24.96	33.47
.60	.61	516	0.31	12.63	26.40	-30.91	44.75

8,650 comparison are excluded, because their cross correlation level is outside the limits of the table.