SONIC/DENSITY WELL LOG DATA EDITING WITH PSEUDO CURVE GENERATION-

INDONESIAN EXAMPLES USING A MULTIPLE CROSSPRODUCT NON-LINEAR METHOD

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ABSTRACT

Sonic and density well log data are vital for geophysicists, petrophysicists, engineers and geologists in the search and evaluation of economic oil and gas reserves. In many cases, however, the data are missing or need editing due to environmental effects such as sonic cycle skipping or density rugose hole and washout effects. In the past, most methods relied on manual well log editing or pseudo curve generation using single logs. A new method, that automatically edits sonic and density logs and that generates pseudo curves from combinations of other logs, has been developed. By incorporating the crossproducts of multiple curves as an addition to the conventional linear multiple regression techniques, more accurate non-linear data correlations can be obtained which yield better results.

Preliminary applications of this new approach include improved synthetic seismograms, pseudo sonic/density log predictions, replacement of bad or missing well log data, calibration of logs to core data, and better well log quality control. For example, gamma ray, density and neutron data may be calibrated to generate a pseudo sonic curve that can be used in places where the sonic is missing or bad.

This method has been tested in Indonesia over the last few years and several examples demonstrate the benefits and advantages of using this approach. Additional future applications such as permeability estimations and production prediction may also be possible.

PROGRAM APPLICATIONS:

1. Well Log Data Quality Control
2. Edit Sonic Logs to Remove Cycle Skips
3. Edit Density Logs for Borehole Washout Effects
4. Edit Other Logs for Environmental Effects
5. Verify Questionable Log Responses
6. Generate Curves to Replace Bad or Missing Data
7. Sonic Log Prediction
8. Calibrate Logs to Core Data and Generate Data in Non-Cored Zones
9. Other Applications - Possible DST, Production Prediction

PROGRAM DESCRIPTION:

The automatic curve editing and generating program is divided into two separate parts:

STEP 1: (**ACECAL-**Automatic Curve Editing and Calibration)

The **ACECAL** program calibrates three input curves to a fourth input reference curve to determine coefficients that can be applied to the three input curves for generating a new reference curve using STEP 2.

STEP 2: (**ACEGEN-**Automatic Curve Editing and Generation)

The **ACEGEN** program applies the coefficients previously determined from **ACECAL** to the three input curves to generate a new reference curve that can be used to replace the original reference curve.

PROGRAM METHOD:

A reference curve such as a sonic, density, etc. is selected for editing or calibration. Three other curves that are anticipated to have some reasonable correlation to the reference curve are then chosen for calibration to the reference curve over intervals containing good quality data. The program **ACECAL** calculates the coefficients that best fit the correlation curves to the reference curve according to a special non-linear multiple regression technique described in the appendix. The program **ACEGEN** uses the results of the **ACECAL** program to manufacture a new corrected or synthetic curve that can be used to replace or fill in the reference curve.

ACECAL PROGRAM: (STEP 1 - CALIBRATION)

PROGRAM OPTIONS:

1. Reference curve is selected for editing or calibration
2. Three input curves may be chosen for calibration to reference curve
3. Discriminator curve may be used to include certain ranges of data
4. A second discriminator curve may be used to exclude certain ranges of data
5. Data normalization is optional
6. A logarithmic function may be selected for the reference curve if desired
7. Sample increment may be chosen to skip samples
8. Noise damping factor is optional

PROGRAM PARAMETERS:

CURVE1IN	- First input curve name
CURVE2IN	- Second input curve name
CURVE3IN	- Third input curve name
CURVE EDIT	- Reference curve to be edited or generated
DEPTH CRV	- Depth curve name
CURVINCLUD	- Discriminator curve used to include data
CURVEXCLUD	- Discriminator curve used to exclude data
NORMALIZE	- Flag to automatically normalize data
LOGARITHM	- Flag to use logarithm of reference curve
START DEP	- Top starting depth for calibration
STOP DEP	- Bottom stopping depth for calibration
INCLUD MIN	- Minimum value of CURVINCLUD for discrimination
INCLUD MAX	- Maximum value of CURVINCLUD for discrimination
EXCLUD MIN	- Minimum value of CURVEXCLUD for discrimination
EXCLUD MAX	- Maximum value of CURVEXCLUD for discrimination
STEP INCR.	- Step depth increment for selecting samples
NOISE %	- Percent noise factor for damping/stabilization

PROGRAM OUTPUT CURVES:

FLAGZ	- Curve which has a value of 1 over the zones used for calibration
NX	- A curve that represents the cumulative number of calibration points

PROGRAM OUTPUT FILE:

CURVECAL.OUT	-Output file containing the coefficients and statistical parameters

ACEGEN PROGRAM: (STEP 2 - GENERATION)

PROGRAM OPTIONS:

1. Same reference curve is selected for editing or generation as chosen in **ACECAL** (If no reference curve is available, DEPTH can be used to generate a new one)
2. Same three input curves are selected as chosen in **ACECAL**
3. Reference curve may be increased and/or decreased in value
4. A logarithmic function may be selected for the reference curve if also chosen on **ACECAL** program
5. A maximum difference between the original reference and new computed curve may be chosen for selective editing
6. A discriminator curve may be chosen for selective zone editing

PROGRAM PARAMETERS:

CURVE1IN	- First input curve name
CURVE2IN	- Second input curve name
CURVE3IN	- Third input curve name
CURVE EDIT	- Reference curve to be edited or generated
DISCRIM.	- Discriminator curve for curve generation
INCREASE	- Flag for generated curve to only increase in value
DECREASE	- Flag for generated curve to only decrease in value
LOGARITHM	- Flag to use logarithm of reference curve
DIFF. MAX	- Maximum difference between computed curve and reference curve. (used to prorate or totally replace the reference curve in zones where the difference exceeds this value)
DISC. MIN	- Minimum value of discriminator curve
DISC. MAX	- Maximum value of discriminator curve

PROGRAM OUTPUT CURVES:

CURVECAL	- Curve computed from coefficients
CURVENEW	- The new edited or generated reference curve
EDITFACT	- A factor between 0 and 1 that indicates the ratio of the difference between the new and the original curve to the maximum difference selected. Used for quality control and to reduce abrupt changes at edited boundaries.

(SEE APPENDIX FOR THEORETICAL DETAILS)

EXAMPLE:

A comparison of a synthetic seismogram computed from a real sonic versus one computed from the pseudo-sonic generated from the **ACECAL** and **ACEGEN** programs is shown in **Figure 1**. The pseudo-sonic was computed using the gamma ray (clay volume), density and neutron logs, from logging-while-drilling (LWD) measurements. The calibration was determined using combined data from four nearby wells and the **ACECAL** output results are listed below.

CALIBRATION RESULTS FROM ACECAL PROGRAM:

Y=SONIC TRAVEL TIME (μSEC/FT)
X1=CLAY VOLUME (DECIMAL, FROM GAMMA RAY)
X2=DENSITY (G/CC)
X3=NEUTRON POROSITY (LIMESTONE DECIMAL UNITS)

CALIBRATION COEFFICIENTS:

a0= 36.1781946574
a1= 6.5839349814
a2= 8.6390224654
a3=104.2473527381
a4= -5.2942970401
a5= 38.2546658105
a6= 26.2068481686
a7= -2.8478019209

COEFFICIENT OF DETERMINATION (R**2)= .562
COEFFICIENT OF MULTIPLE CORRELATION (R)= .750
STANDARD ERROR OF ESTIMATE= 11.516 μSEC/FT

The pseudo-sonic curve was computed using **ACEGEN** to apply the above calibration coefficients. From **Figure 1** there is an excellent agreement between the real vs. pseudo-sonic generated seismograms.

APPENDIX:

Conventional multiple linear regression uses the following general form: [1]

$$Y = A_0 + \sum_{i=1}^{n} A_i X_i \qquad .....(1)$$

where Y is the dependent variable, X_i are the independent variables, A_0 is a constant, A_i are the coefficient constants, and *n* is the number of independent variables.

The Automatic Curve Editing, Calibration and Generation programs, **ACECAL** and **ACEGEN,** are based on the same principles generally used with multiple linear regression, but provide a much better correlation by allowing the linear coefficients to vary as functions of the input curve values. This technique leads to the use of inter-variable cross products of the input curves and effectively provides additional variables that enhance the correlation process. For instance, in the standard multiple linear regression approach, a reference curve "Y" can be calibrated to three input curves "X1, X2, and X3" to determine an equation of best fit such as:

Y = A0 + A1*X1 + A2*X2 + A3*X3 .....(2)

where:

A0, A1, A2, and A3 are coefficient constants.

However, if the coefficients A1, A2, and A3 are allowed to vary as linear functions of the other input curves, then cross products of the variables are generated that can be used as additional input curves. Tests were initially made assuming A1 to be a linear function of X2 and X3, with A2 a function of X1 and X3, and with A3 a function of X1 and X2, etc.:

For example letting:

A0 = a0 .....(3)

A1 = f(X2,X3) = a10 + a12*X2 + a13*X3 .....(4)

A2 = f(X1,X3) = a20 + a21*X1 + a23*X3 .....(5)

A3 = f(X1,X2) = a30 + a31*X1 + a32*X2 .....(6)

leads to new coefficients a0,...a6 with additional cross products:

Y = a0+a1*X1+a2*X2+a3*X3+a4*X1*X2+a5*X1*X3+a6*X2*X3 .....(7)

where:

a0 = a0 .....(8)

a1 = a10 .....(9)

a2 = a20 ...(10)

a3 = a30 ...(11)

a4 = a12 + a21 ...(12)

a5 = a13 + a31 ...(13)

a6 = a23 + a32 ...(14)

Tests made using equation (7) yielded improved correlation coefficients with less standard error of estimate when compared to the ones using equations (1) or (2).

The Automatic Curve Editing and Generating program (**ACEGEN**) that is being tested currently adds a triple cross product of X1*X2*X3 to yield a total of seven variables plus one constant and appears to be a slight improvement over equation (7):

$$Y = a0+a1*X1+a2*X2+a3*X3+a4*X1*X2+a5*X1*X3+a6*X2*X3+a7*X1*X2*X3 \qquad ...(15)$$

The use of the multiple cross products appears to fit a wider range of curve shapes and to provide a more accurate correlation than by using only straight multiple linear regression. Further improvements may be obtained by expanding the process to include more than three variables. Equation (15) is the one currently being used with linear and logarithmic reference curve options as part of the ACECAL and ACEGEN programs.

PROGRAM HISTORY:

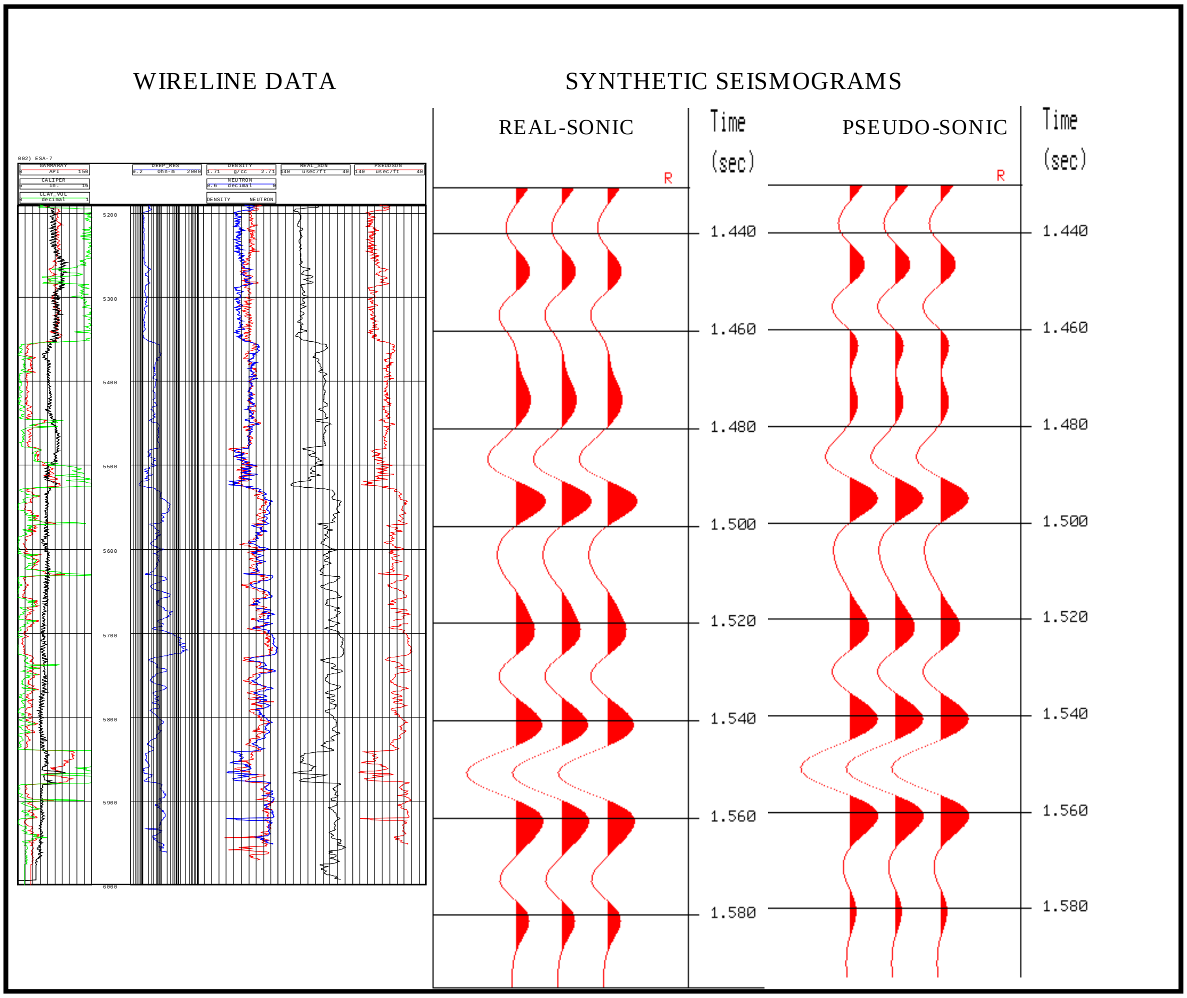
Original code developed by T.D. Lawrence and converted to FORTRAN for use as a user program on the PC based PETCOM Log Analysis System. Options for normalization and noise damping added using code provided by Vaughn Ball.

ACKNOWLEDGMENTS:

The authors would like to thank PERTAMINA, Atlantic Richfield Indonesia, Inc. and all Northwest Java PSC partners for permission to present this poster session. We also acknowledge the special help of the Wayne Suyenaga and Vaughn Ball in this endeavor. Additional encouragement was received from ARCO Indonesia management, including John R. Duncan and Firman A. Yaman. Support from ARCO management in Plano is also appreciated.

REFERENCES:

1. *Numerical Recipes*, Cambridge University Press, 1992. pp. 509-515.



COMPARISON OF SYNTHETIC SEISMOGRAMS: REAL-SONIC VS. PSEUDO-SONIC

PROGRAM DESCRIPTION:

The automatic curve editing and generating program is divided into two separate parts:

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STEP 2: (ACEGEN-Automatic Curve Editing and Generation)

The ACEGEN program applies the coefficients previously determined from ACECAL to the three input curves to generate a new reference curve that can be used to replace the original reference curve.

PROGRAM METHOD:

A **reference** curve such as a sonic, density, etc. is selected for editing or calibration. **Three other** curves that are anticipated to have some reasonable correlation to the reference curve are then chosen for calibration to the reference curve over intervals containing good quality data. The program **ACECAL** calculates the coefficients that best fit the correlation curves to the reference curve according to a special non-linear multiple regression technique described in the appendix. The program **ACEGEN** uses the results of the **ACECAL** program to manufacture a **new** corrected or **synthetic** curve that can be used to replace or fill in the reference curve.

ACECAL PROGRAM: (STEP 1 - CALIBRATION)
PROGRAM OPTIONS:

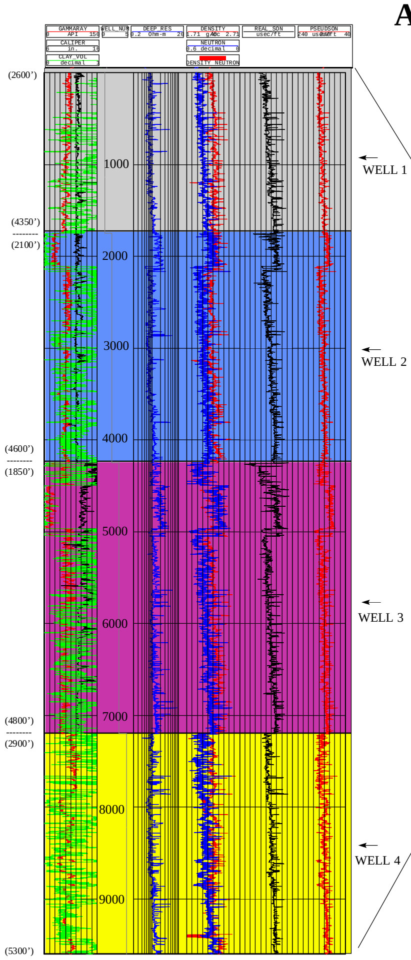
1. Reference curve is selected for editing or calibration
2. Three input curves may be chosen for calibration to reference curve
3. Discriminator curve may be used to include certain ranges of data
4. A second discriminator curve may be used to exclude certain ranges of data
5. Data normalization is optional
6. A logarithmic function may be selected for the reference curve if desired
7. Sample increment may be chosen to skip samples
8. Noise damping factor is optional

ACEGEN PROGRAM: (STEP 2 - GENERATION)

PROGRAM OPTIONS:

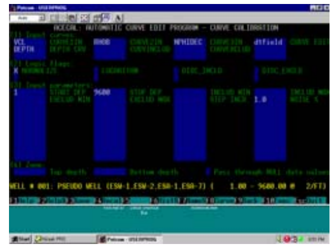
1. Same reference curve is selected for editing or generation as chosen in ACECAL (If no reference curve is available, DEPTH can be used to
2. Same three input curves are selected as chosen in ACECAL
3. Reference curve may be increased and/or decreased in value
4. A logarithmic function may be selected for the reference curve if also chosen on ACECAL program
5. A maximum difference between the original reference and new computed curve may be chosen for selective editing
6. A discriminator curve may be chosen for selective zone editing

ACECAL PROGRAM



YIELD

EXAMPLE:
DATA FROM 4 WELLS COMBINED FOR CALIBRATION



CALIBRATION RESULTS COEFFICIENTS:

a0 = 36.1781946574
a1 = 6.5839349814
a2 = 8.6390224654
a3 = 104.2473527381
a4 = -5.2942970401
a5 = 38.2546658105
a6 = 26.2068481686
a7 = -2.8478019209

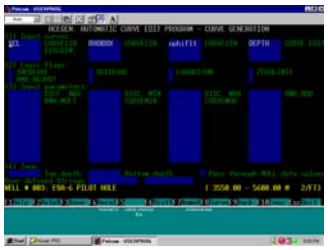
COEFFICIENT OF DETERMINATION(R**2)= .562
COEFFICIENT OF MULTIPLE CORRELATION(R)= .750
STANDARD ERROR OF ESTIMATE= 11.516
STARTING DEPTH= 1.000
STOPPING DEPTH= 9600.000
NUMBER OF POINTS= 19099.

Y=a0+a1*X1+a2*X2+a3*X3+a4*X1*X2+a5*X1*X3+a6*X2*X3+a7*X1*X2*X3
where:
Y=Sonic Travel Time
X1=Clay Volume (decimal from Gamma Ray)
X2=Density (g/cm3)
X3=Neutron (decimal porosity units)

ACEGEN PROGRAM

EXAMPLE:PSEUDO SONIC GENERATED FROM PREVIOUS CALIBRATION

LWD Logs Only



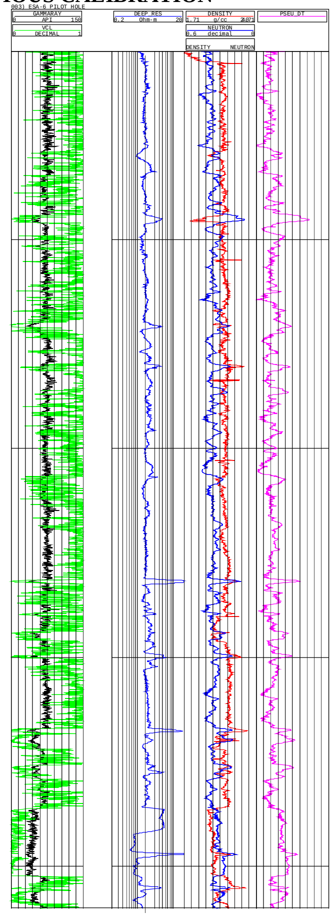
CALIBRATION RESULTS COEFFICIENTS:

a0 = 36.1781946574
a1 = 6.5839349814
a2 = 8.6390224654
a3 = 104.2473527381
a4 = -5.2942970401
a5 = 38.2546658105
a6 = 26.2068481686
a7 = -2.8478019209

COEFFICIENT OF DETERMINATION(R**2)= .562
COEFFICIENT OF MULTIPLE CORRELATION(R)= .750
STANDARD ERROR OF ESTIMATE= 11.516
STARTING DEPTH= 1.000
STOPPING DEPTH= 9600.000
NUMBER OF POINTS= 19099.

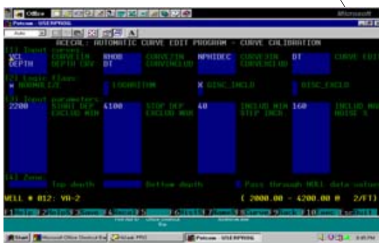
Y=a0+a1*X1+a2*X2+a3*X3+a4*X1*X2+a5*X1*X3+a6*X2*X3+a7*X1*X2*X3
where:
Y=Calculated Pseudo-Sonic Travel Time
X1=Clay Volume (decimal from Gamma Ray)
X2=Density (g/cm3)
X3=Neutron (decimal porosity units)

YIELD



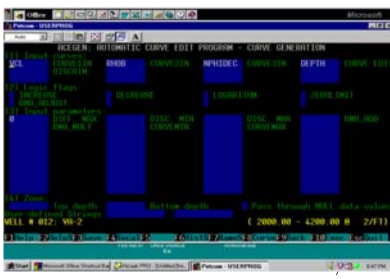
AUTOMATIC CYCLE SKIP REMOVAL

EXAMPLE: FIELD ARRAY SONIC LOG CYCLE SKIPS REMOVED USING ACECAL/ACEGEN ACCURACY CONFIRMED LATER BY STC WAVEFORM PROCESSING

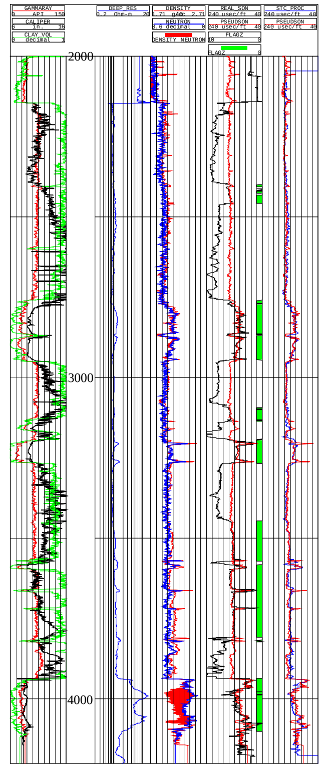


CALIBRATION RESULTS COEFFICIENTS

a0 = 504.2288394385
a1 = -25.3889549837
a2 = -183.1088340463
a3 = -386.5522424022
a4 = 27.3621813275
a5 = 20.5341463046
a6 = 186.8900451564
a7 = -15.6310895149
COEFFICIENT OF DETERMINATION(R**2)= .698
COEFFICIENT OF MULTIPLE CORRELATION(R)= .836
STANDARD ERROR OF ESTIMATE= 11.837
STARTING DEPTH= 2200.000
STOPPING DEPTH= 4100.000
NUMBER OF POINTS= 1693.
CURVE_INCLUDE=DT
INCLMIN=40
INCLMAX=160



YIELD



Y=a0+a1*X1+a2*X2+a3*X3+a4*X1*X2+a5*X1*X3+a6*X2*X3+a7*X1*X2*X3
where:
Y=Calculated Pseudo-Sonic Travel Time
X1=Clay Volume (decimal from Gamma Ray)
X2=Density (g/cm3)
X3=Neutron (decimal porosity units)

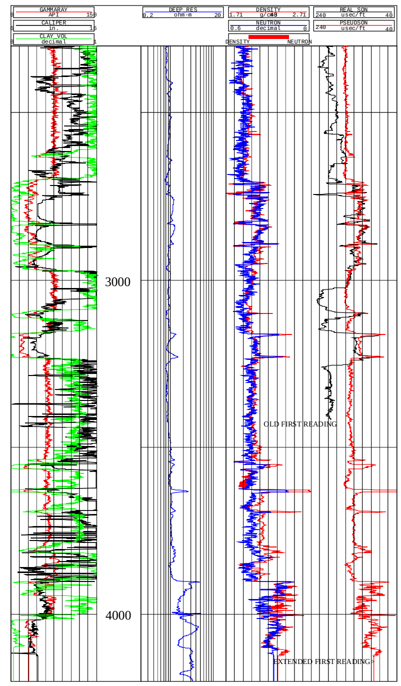
OFFSET WELL DEPTH EXTENSION / AUTOMATIC CYCLE SKIP REMOVAL

EXAMPLE: FIELD ARRAY SONIC LOG EXTENDED IN DEPTH AND CYCLE SKIPS REMOVED USING CALIBRATIONS FROM OFFSET WELL

CALIBRATION RESULTS COEFFICIENTS
(FROM PREVIOUS OFFSET WELL)

a0 = 504.2288394385
a1 = -25.3889549837
a2 = -183.1088340463
a3 = -386.5522424022
a4 = 27.3621813275
a5 = 20.5341463046
a6 = 186.8900451564
a7 = -15.6310895149
COEFFICIENT OF DETERMINATION(R**2)= .698
COEFFICIENT OF MULTIPLE CORRELATION(R)= .836
STANDARD ERROR OF ESTIMATE= 11.837
STARTING DEPTH= 2200.000
STOPPING DEPTH= 4100.000
NUMBER OF POINTS= 1693.
CURVE_INCLUDE=DT
INCLMIN=40
INCLMAX=160

YIELD



Y=a0+a1*X1+a2*X2+a3*X3+a4*X1*X2+a5*X1*X3+a6*X2*X3+a7*X1*X2*X3
where:
Y=Calculated Pseudo-Sonic Travel Time
X1=Clay Volume (decimal from Gamma Ray)
X2=Density (g/cm3)
X3=Neutron (decimal porosity units)

ACECAL VS. CONVENTIONAL REGRESSION

CONVENTIONAL LINEAR REGRESSION

Conventional multiple linear regression uses the following general form:

$$Y = A0 + \sum_{i=1}^{n} AiXi$$

or

Y=a0+a1*X1+a2*X2+a3*X3

ACECAL

Y=a0+a1*X1+a2*X2+a3*X3+a4*X1*X2+a5*X1*X3+a6*X2*X3+a7*X1*X2*X3

where:
Y=Calculated Pseudo-Sonic Travel Time
X1=Clay Volume (decimal from Gamma Ray)
X2=Density (g/cm3)
X3=Neutron (decimal porosity units)