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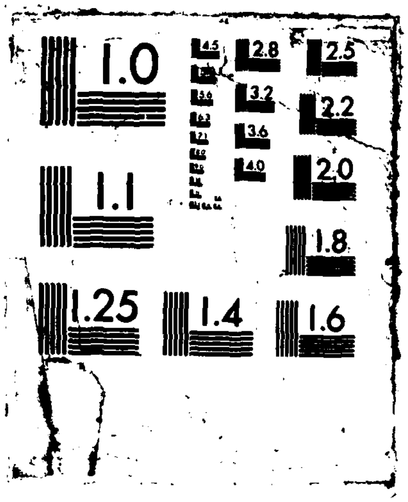
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RADC-TR-87-156
In-House Report
September 1987

ANALYSIS OF THE INTER-LAYER INDEPENDENCE OF STELLAR SCINTILLOMETER PROFILES OF C_n^2

Donald M. Stebbins

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
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C_n^2 profiles from nine data collection efforts using the NOAA stellar scintillometer have been examined to assess the statistical independence for C_n^2 values from separated altitude layers. Linear correlation coefficients between C_n^2 values have been calculated for all combinations of layer pairs for both short and long term time periods. The tendency of measured C_n^2 values for different layers to synchronously rise or fall has also been evaluated. Results indicate that the C_n^2 data fails several tests of layer independency and that the data may be invalid at least at some altitudes. [illegible]

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1. Introduction

For the past 10 years, the stellar scintillometer built by the National Oceanic and Atmospheric Administration (NOAA) has been used by several research groups to collect profiles of C_n^2 (the atmospheric index of refraction structure function parameter) in various locations. (Table 1 lists the locations and time periods of the data collection efforts included in this investigation.) RADC (OCSP) has been studying the data from these efforts to determine the statistical behavior of C_n^2 as a function of time, location, and other parameters. Among the original purposes was an assessment of the log-normality of the distribution of C_n^2 data as a function of the time duration of the measurement period.[1] The distribution had been found nearly log-normal in earlier investigations.[2]

Preliminary analyses included calculations of the correlation coefficients between the seven values of C_n^2 contained in each profile. These results strongly indicated that there is inordinately high correlation between the C_n^2 levels at the seven altitude regions. For that reason, we have conducted a more detailed analysis of the correlation behavior of the data for all the data collection periods.

2. Stellar Scintillometer

The NOAA scintillometer consists basically of a 36-cm catadioptric telescope and a partially transmitting, partially reflecting variable spatial frequency filter which directs starlight to each of two photomultiplier tubes. Detailed descriptions of the instrument and its theory of operation are available in references 3 and 4. The scintillometer and associated software produce values for C_n^2 at seven slant ranges along a line between the instrument and a source star. If the star is near the zenith, this translates into seven altitude regions in the atmosphere between approximately 2 and 18 km. (the layer numbers and associated height regions are shown in table 2.) The seven measurements are not independent because the weighting functions used to separate the spatial frequencies overlap for adjacent layers, and, to lesser extent, for layers separated by one layer. It has been customarily assumed that layers 1, 4, and 7 are independent, so that, in theory, the instrument provides three independent measurements of atmospheric turbulence.

3. Layer Independence Analysis

The primary objective of this analysis is to determine whether the turbulence data collected with the NOAA scintillometers exhibits the predicted layer independence. Several tests of layer independence have been applied, including correlation analysis and evaluation of inter-profile variation patterns.

3.a. Inter-layer Correlation Coefficients

Correlation coefficients between C_n^2 values at all combinations of pairs of altitude layers have been calculated according to the standard correlation formula. Calculations were made for both the linear and natural logarithmic values for all the data collections and for all the data taken as a whole. Analysis of the data from a number of profile gathering efforts indicates that there is a moderate to strong linear correlation between the layers, even between layers 1 and 7 for almost all the data collections. (See tables 3 through 22.) Only the data from the RADC scintillometer during the May 1986 experiment at Penn State does not show correlation between all layers. (This data appears to be bipolar, with layers 1 through 3 correlating, and layers 4 through 7 correlating with each other but not with the lowest three layers.) Given the number of measurements there is an infinitesimally small probability of these correlations occurring by chance.

The correlation coefficients calculated in the preceding analysis are influenced by both long and short term effects. In some instances the correlation could be caused by long term (climatically induced) variations in the magnitude of the turbulence affecting widely separated altitude regions. In other words, there are high turbulence nights and low turbulence nights on which all layers are higher or lower than average. Correlation of this nature is assumed by models which show C_n^2 dependent only on height. The AFGL data from early May appears to fit into that situation.[5,6] Tables 23 through 26 show relatively low correlation coefficients for the three day periods taken separately, while tables 7 and 8 show higher correlation coefficients for the combined data for the six night period. It should be pointed out that the apparent climatical change could in fact be due to an instrumental bias affecting all or most altitudes.

In order to eliminate the long term effects, the correlation coefficients have been calculated for each night of operation on which more than 10 valid profiles were obtained. The average correlation coefficients from 111 nights of data are shown on tables 27 and 28. While these coefficients are generally lower than the coefficients including long term effects, they are significantly higher than would be expected from independent C_n^2 measurements. The pattern of the average coefficients can generally be described as showing statistically significant positive correlation which decreases with level separation. (The only deviation from the pattern is that correlation between the lowest two layers and layers 4, 5 and 6 remains virtually constant.) This pattern is consistent with the pattern expected if the correlation were primarily caused by the instrument.

3.b. Inter-profile Variations

An alternative method of assessing whether the C_n^2 values at separated altitudes are statistically independent is to determine the tendency of the C_n^2 values from different layers to rise or fall together from one profile to the next. If the C_n^2 values are truly random, independent variables, one would expect the C_n^2 values to vary in the same direction 50 per cent of the time. Calculations were made by subtracting each C_n^2 measured value from the previous measurement at the same altitude and comparing the signs of the results. Only those measurements separated by less than ten minutes were included. As the accompanying tables (29 through 38) indicate, the C_n^2 values appear to synchronously rise or fall much more frequently than expected, except for pairs including layer 7. (The standard deviation from the expected mean of 0.5 is shown at the bottom of each table in terms of percentage. For example, table 29 shows that layers 1 and 4 vary the same way 64 percent of the time. With a standard deviation of 0.8 percent, the actual percentage is over seventeen standard deviations away from the expected value.) This is a strong indication that the C_n^2 values at the separated layers are not independent. This analysis is independent of any long term trends in the data. There is no known physical phenomenon to account for short term correlation.

From the tables, it can be seen that there is a definite pattern to the percentages. The directions of change at the high altitude levels appear to be most closely coupled with the direction of change at the lowest altitude. This pattern suggests that the turbulence measurements at the higher altitudes may be dominated by a signal associated with turbulence at the lowest altitude. However, it can also be noted that the inter-layer percentages vary little among the data collections, indicating that the coupling between the altitude regions is not dependent on the location, time of year, turbulence strength or other parameters. This pattern suggests that the measured changes in turbulence strength are produced by signals internal to the device and not linked to the environment.

Although the test of direction of variation is free of long term effects, it does have the liability of not including the amplitude of the differences from one profile to the next. In order to assess whether the size as well as the direction of the inter-profile deltas track between the separated layers, the correlation coefficients for the deltas themselves have been calculated. Results are presented for both linear and logarithmic data for the combined data set. Tables 39 and 40 show that there is, in general, fairly strong positive correlation between the amplitudes of the deltas for even widely separated layers, especially in the case of linear turbulence values. These results suggest that the inter-profile changes in C_n^2 at widely separated layers are not independent and appear to be strongly linked.

4. Conclusions

The preceding analyses have determined that the C_n^2 values produced by the scintillometer fail several tests of the independence of the widely separated layers. There is no known physical phenomenon to account for these results, and data from other techniques have not shown similar tendencies. Radar measurements of C_n^2 taken at Penn State during the May 1986 observation period do not show any higher correlation between layers than can be explained by pure chance.[7]

The lack of independence and other characteristics of the data are indications that, at least at some altitudes, the measured C_n^2 values are invalid. The signal output used to generate the C_n^2 values appears to be corrupted by a signal or noise affecting all or most layers. The source of the corrupting signal could be either internal to the device or associated with turbulence at the lowest altitude.

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5. E.A. Murphy, and F. P. Battles, "Isoplanatic Angle from Stellar Scintillometer Measurements of Cn2 at Kirtland AFB, NM." AFGL Technical Memorandum no. 129, 1986.

6. F. P. Battles, "Correlation Coefficients for Cn2 Based on Stellar Scintillometer Measurements." Massachusetts Maritime Academy Research Report no. 3-12-87, 1987.

7. M. Moss, Penn State U., Informal communication, Jan 1987.

Data Collection Information

Table 1

Organization and Location	Time Period	No. of Nights and Profiles
RADC, Penn State U.	May, 1986	5 - 140
AFGL, Penn State U.	May, 1986	6 - 192
RADC, Maui	Apr, 1985	8 - 157
AVCO(AMOS), Maui	Feb-Apr, 1985	19 - 1011
RADC, MacDonald Obs., TX	Jan, 1985	5 - 118
RADC, Verona, NY	Apr-Oct, 1982	9 - 475
RADC, Verona, NY	Apr-Dec, 1980	25 - 788
RADC(AMOS), Maui	Mar, 1979-Jul, 1980	16 - 594
AFWL, White Sands, NM	May-Nov, 1977	26 - 802

Nominal Altitude Regions

Table 2

Layer Number	Nominal Altitude Region
1	2.2 km.
2	3.4 km.
3	5.2 km.
4	7.3 km.
5	9.4 km.
6	14.0 km.
7	18.5 km.

Tables 3 - 26 Inter-layer Correlation Coefficients

Table 3

Correlation coefficients between C_n^2 values for pairs of layers.

ALL DATA - 4279 Profiles Linear Data

	1	2	3	4	5	6	7
1		0.97	0.92	0.57	0.56	0.64	0.60
2			0.96	0.58	0.51	0.64	0.58
3				0.66	0.57	0.66	0.61
4					0.89	0.74	0.70
5						0.78	0.70
6							0.86

Table 4

Correlation coefficients between C_n^2 values for pairs of layers.

ALL DATA - 4279 Profiles Log Data

	1	2	3	4	5	6	7
1		0.94	0.68	0.54	0.48	0.51	0.44
2			0.78	0.63	0.56	0.58	0.50
3				0.68	0.61	0.56	0.46
4					0.90	0.69	0.60
5						0.80	0.64
6							0.81

Table 5

Correlation coefficients between C_n^2 values for pairs of layers.

RADC - Penn State (1986) 140 Profiles Linear Data

	1	2	3	4	5	6	7
1		0.99	0.88	-0.12	-0.21	-0.20	-0.25
2			0.93	-0.01	-0.09	-0.11	-0.20
3				0.34	0.23	0.15	0.01
4					0.93	0.73	0.49
5						0.84	0.44
6							0.51

Table 6

Correlation coefficients between C_n^2 values for pairs of layers.

RADC - Penn State (1986) 140 Profiles Log Data

	1	2	3	4	5	6	7
1		0.97	0.83	-0.01	-0.01	-0.09	-0.21
2			0.92	0.16	0.08	0.04	-0.12
3				0.48	0.38	0.28	0.07
4					0.90	0.70	0.49
5						0.83	0.43
6							0.49

Table 7

Correlation coefficients between C_n^2 values.
for pairs of layers.

AFGL - Penn State (1986) 192 Profiles Linear Data

	1	2	3	4	5	6	7
1		0.91	0.80	0.39	0.46	0.25	0.29
2			0.93	0.50	0.54	0.33	0.34
3				0.67	0.63	0.27	0.31
4					0.77	0.30	0.40
5						0.42	0.56
6							0.61

Table 8

Correlation coefficients between C_n^2 values
for pairs of layers.

AFGL - Penn State (1986) 192 Profiles Log Data

	1	2	3	4	5	6	7
1		0.87	0.75	0.54	0.61	0.60	0.53
2			0.92	0.65	0.64	0.51	0.43
3				0.76	0.69	0.47	0.40
4					0.74	0.41	0.39
5						0.54	0.52
6							0.59

Table 9

Correlation coefficients between C_n^2 values
for pairs of layers.

RADC Maui (1985) 157 Profiles Linear Data

	1	2	3	4	5	6	7
1		0.97	0.94	0.91	0.92	0.86	0.84
2			0.99	0.91	0.83	0.89	0.84
3				0.93	0.80	0.89	0.86
4					0.90	0.85	0.88
5						0.79	0.79
6							0.91

Table 10

Correlation coefficients between C_n^2 values
for pairs of layers.

RADC Maui (1985) 157 Profiles Log Data

	1	2	3	4	5	6	7
1		0.99	0.97	0.90	0.90	0.88	0.88
2			0.99	0.92	0.90	0.89	0.89
3				0.95	0.92	0.91	0.90
4					0.96	0.90	0.87
5						0.94	0.87
6							0.93

Table 11

Correlation coefficients between C_n^2 values.
for pairs of layers.

AVCO MAUI (1985) 1011 Profiles Linear Data

	1	2	3	4	5	6	7
1		0.83	0.79	0.51	0.55	0.66	0.65
2			0.91	0.58	0.59	0.68	0.66
3				0.79	0.76	0.73	0.67
4					0.93	0.59	0.49
5						0.73	0.57
6							0.80

Table 12

Correlation coefficients between C_n^2 values
for pairs of layers.

AVCO Maui (1985) 1011 Profiles Log Data

	1	2	3	4	5	6	7
1		0.93	0.92	0.68	0.71	0.85	0.81
2			0.97	0.67	0.69	0.81	0.78
3				0.82	0.81	0.85	0.79
4					0.91	0.82	0.70
5						0.90	0.82
6							0.83

Table 13

Correlation Coefficients between C_n^2 values. for pairs of layers.

MacDonald Obs. (1985) 118 Profiles Linear Data

	1	2	3	4	5	6	7
1		1.0	1.0	0.72	0.42	0.83	0.78
2			1.0	0.73	0.43	0.83	0.79
3				0.76	0.46	0.84	0.80
4					0.90	0.89	0.78
5						0.78	0.61
6							0.88

Table 14

Correlation Coefficients between C_n^2 values for pairs of layers.

MacDonald Obs. (1985) 118 Profiles Log Data

	1	2	3	4	5	6	7
1		0.98	0.84	0.67	0.51	0.70	0.58
2			0.98	0.70	0.53	0.69	0.59
3				0.78	0.61	0.73	0.60
4					0.94	0.75	0.51
5						0.78	0.48
6							0.73

Table 15

Correlation coefficients between C_n^2 values for pairs of layers.

Verona (1982) 475 Profiles Linear Data

	1	2	3	4	5	6	7
1		0.99	0.98	0.70	0.62	0.71	0.65
2			0.99	0.73	0.64	0.71	0.66
3				0.78	0.68	0.74	0.69
4					0.90	0.72	0.65
5						0.81	0.62
6							0.82

Table 16

Correlation coefficients between C_n^2 values for pairs of layers.

Verona (1982) 475 Profiles Log Data

	1	2	3	4	5	6	7
1		0.96	0.96	0.65	0.57	0.64	0.60
2			0.97	0.70	0.62	0.66	0.60
3				0.79	0.69	0.71	0.65
4					0.87	0.80	0.65
5						0.89	0.75
6							0.87

Table 17

Correlation coefficients between C_n^2 values for pairs of layers.

Verona (1980) 788 Profiles Linear Data

	1	2	3	4	5	6	7
1		0.93	0.83	0.65	0.69	0.56	0.42
2			0.94	0.79	0.80	0.66	0.56
3				0.94	0.91	0.72	0.65
4					0.96	0.72	0.68
5						0.81	0.65
6							0.77

Table 18

Correlation coefficients between C_n^2 values for pairs of layers.

Verona (1980) 788 Profiles Log Data

	1	2	3	4	5	6	7
1		0.96	0.90	0.74	0.75	0.64	0.41
2			0.97	0.82	0.80	0.68	0.48
3				0.92	0.87	0.49	0.51
4					0.96	0.71	0.53
5						0.81	0.54
6							0.67

Table 19

Correlation coefficients between C_n^2 values for pairs of layers.

Maui 1979-1980 594 Profiles Linear data

	1	2	3	4	5	6	7
1		0.89	0.80	0.66	0.77	0.83	0.74
2			0.94	0.69	0.73	0.70	0.58
3				0.83	0.77	0.63	0.51
4					0.90	0.58	0.43
5						0.76	0.53
6							0.83

Table 20

Correlation coefficients between C_n^2 values for pairs of layers.

Maui (1979-1980) 594 Profiles Log Data

	1	2	3	4	5	6	7
1		0.94	0.89	0.64	0.60	0.76	0.50
2			0.96	0.57	0.59	0.66	0.54
3				0.64	0.50	0.59	0.48
4					0.93	0.70	0.47
5						0.81	0.51
6							0.70

Table 21

Correlation Coefficients between C_n^2 values for pairs of layers.

AFWL - White Sands (1977) 802 Profiles Linear Data

	1	2	3	4	5	6	7
1		0.93	0.57	0.53	0.52	0.61	0.55
2			0.60	0.49	0.44	0.52	0.45
3				0.40	0.29	0.33	0.23
4					0.67	0.51	0.43
5						0.67	0.50
6							0.75

Table 22

Correlation coefficients between C_n^2 values for pairs of layers.

AFWL (1977) 802 Profiles Log Data

	1	2	3	4	5	6	7
1		0.94	0.4	0.53	0.48	0.55	0.46
2			0.49	0.45	0.36	0.45	0.36
3				0.36	0.20	0.23	0.14
4					0.75	0.39	0.42
5						0.59	0.45
6							0.72

Table 23

Correlation coefficients between C_n^2 values
for pairs of layers.

AFGL - Penn State (May 1- 3, 1986) 107 Profiles Linear Data

	1	2	3	4	5	6	7
1		0.91	0.77	0.20	0.23	-0.01	0.07
2			0.89	0.26	0.30	0.08	0.14
3				0.52	0.49	0.04	0.14
4					0.70	0.04	0.26
5						0.08	0.42
6							0.45

Table 24

Correlation coefficients between C_n^2 values
for pairs of layers.

AFGL - Penn State (May 1- 3, 1986) 107 Profiles Log Data

	1	2	3	4	5	6	7
1		0.90	0.71	0.07	0.20	0.10	0.29
2			0.87	0.17	0.30	0.18	0.32
3				0.48	0.53	0.21	0.43
4					0.82	0.10	0.36
5						0.13	0.40
6							0.43

Table 25

Correlation Coefficients between C_n^2 values for pairs of layers.

AFGL - Penn State (May 4- 6, 1986) 85 Profiles Linear Data

	1	2	3	4	5	6	7
1		0.87	0.84	0.77	0.68	0.24	0.05
2			0.99	0.85	0.54	0.04	-0.07
3				0.80	0.53	0.01	-0.12
4					0.64	0.12	-0.02
5						0.44	0.11
6							0.53

Table 26

Correlation Coefficients between C_n^2 values for pairs of layers.

AFGL - Penn State (May 4-6, 1986) 85 Profiles Log Data

	1	2	3	4	5	6	7
1		0.64	0.47	0.40	0.40	0.49	0.16
2			0.85	0.64	0.43	0.15	-0.12
3				0.73	0.45	0.07	-0.17
4					0.49	0.16	-0.03
5						0.37	0.18
6							0.38

Average Correlation Coefficients

Table 27

Average correlation coefficients between C_n^2 values.

ALL DATA 111 Nights Linear Data

	1	2	3	4	5	6	7
1		0.89	0.73	0.50	0.52	0.54	0.42
2			0.84	0.52	0.53	0.53	0.39
3				0.70	0.56	0.46	0.35
4					0.79	0.31	0.26
5						0.51	0.18
6							0.49

Average Correlation Coefficients

Table 28

Average correlation coefficients between C_n^2 values.

ALL DATA 111 Nights Log data

	1	2	3	4	5	6	7
1		0.90	0.74	0.49	0.52	0.54	0.39
2			0.83	0.50	0.51	0.53	0.36
3				0.68	0.55	0.45	0.32
4					0.78	0.28	0.21
5						0.48	0.14
6							0.47

Tables 29 - 38 Inter-profile Variation Percentages

Table 29

Percentage of C_n^2 values varying in the same direction for pairs of layers.

ALL DATA 3954 Deltas

	1	2	3	4	5	6	7
1		0.84	0.76	0.64	0.66	0.63	0.51
2			0.80	0.61	0.65	0.63	0.51
3				0.71	0.64	0.59	0.51
4					0.74	0.49	0.48
5						0.60	0.40
6							0.53

Standard deviation = 0.008

Table 30

Percentage of C_n^2 values varying in the same direction for pairs of layers.

RADC - Penn State (1986) 103 Deltas

	1	2	3	4	5	6	7
1		0.89	0.83	0.73	0.79	0.71	0.42
2			0.84	0.70	0.70	0.66	0.49
3				0.79	0.72	0.59	0.47
4					0.79	0.56	0.50
5						0.72	0.41
6							0.39

Standard deviation = 0.049

Table 31

Percentage of C_n^2 values varying in the same direction for pairs of layers.

AFGL - Penn State (1986) 179 Deltas

	1	2	3	4	5	6	7
1		0.83	0.74	0.60	0.60	0.57	0.61
2			0.84	0.65	0.62	0.53	0.58
3				0.69	0.63	0.56	0.53
4					0.71	0.50	0.54
5						0.48	0.56
6							0.56

Standard deviation = 0.037

Table 32

Percentage of C_n^2 values varying in the same direction for pairs of layers.

RADC New Maui (1985) 131 Deltas

	1	2	3	4	5	6	7
1		0.91	0.82	0.70	0.70	0.65	0.55
2			0.86	0.68	0.65	0.65	0.55
3				0.76	0.66	0.63	0.53
4					0.79	0.50	0.48
5						0.56	0.42
6							0.61

Standard deviation = 0.044

Table 33

Percentage of C_n^2 values varying in the same direction for pairs of layers.

AVCO Maui (1985) 961 Deltas

	1	2	3	4	5	6	7
1		0.82	0.80	0.63	0.66	0.63	0.53
2			0.85	0.62	0.65	0.62	0.53
3				0.71	0.65	0.59	0.57
4					0.74	0.47	0.48
5						0.57	0.40
6							0.54

Standard deviation = 0.016

Table 34

Percentage of C_n^2 values varying in the same direction for pairs of layers.

MacDonald Obs. (1985) 110 Deltas

	1	2	3	4	5	6	7
1		0.86	0.84	0.64	0.69	0.63	0.44
2			0.91	0.69	0.72	0.62	0.42
3				0.78	0.76	0.61	0.37
4					0.78	0.53	0.39
5						0.67	0.37
6							0.48

Standard deviation = 0.047

Table 35

Percentage of C_n^2 values varying in the same direction for pairs of layers.

Verona (1982) 458 Deltas

	1	2	3	4	5	6	7
1		0.86	0.82	0.64	0.69	0.59	0.41
2			0.86	0.61	0.66	0.61	0.40
3				0.72	0.66	0.60	0.44
4					0.77	0.51	0.47
5						0.59	0.38
6							0.50

Standard deviation = 0.023

Table 36

Percentage of C_n^2 values varying in the same direction for pairs of layers.

Verona (1980) 741 Deltas

	1	2	3	4	5	6	7
1		0.82	0.75	0.60	0.66	0.62	0.49
2			0.83	0.62	0.64	0.63	0.49
3				0.73	0.69	0.61	0.47
4					0.79	0.52	0.47
5						0.64	0.40
6							0.50

Standard deviation = 0.018

Table 37

Percentage of C_n^2 values varying in same direction for pairs of layers.

Maui, 1979-1980 554 Deltas

	1	2	3	4	5	6	7
1		0.80	0.82	0.68	0.68	0.73	0.58
2			0.73	0.57	0.69	0.70	0.51
3				0.77	0.62	0.64	0.57
4					0.63	0.56	0.56
5						0.67	0.43
6							0.53

Standard deviation = 0.021

Table 38

Percentage of C_n^2 values varying in same direction for pairs of layers.

AFWL (1977) 644 Deltas

	1	2	3	4	5	6	7
1		0.88	0.64	0.62	0.65	0.61	0.52
2			0.67	0.59	0.63	0.63	0.50
3				0.63	0.54	0.53	0.51
4					0.72	0.40	0.46
5						0.53	0.34
6							0.51

Standard deviation = 0.020

Correlation Coefficients between Inter-profile Deltas

Table 39

Correlation coefficients for deltas between successive measurements.

ALL DATA - 3954 Deltas Linear data

	1	2	3	4	5	6	7
1		0.85	0.65	0.34	0.52	0.44	0.39
2			0.81	0.37	0.44	0.48	0.27
3				0.58	0.45	0.38	0.27
4					0.63	0.08	0.15
5						0.29	0.10
6							0.42

Correlation Coefficients between Inter-profile Deltas

Table 40

Correlation coefficients for deltas between successive measurements.

ALL DATA - 3954 Deltas Log data

	1	2	3	4	5	6	7
1		0.81	0.48	0.34	0.40	0.32	0.12
2			0.54	0.38	0.37	0.33	0.10
3				0.44	0.24	0.17	0.08
4					0.60	-0.09	-0.04
5						0.17	-0.25
6							0.12

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