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LONG DURATION MEASUREMENTS OF FADING ON A LOW ELEVATION ANGLE, 11-GHZ SATELLITE PATH

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Abstract - **Some rainfall rate and beacon fade results from the first 5 years of continuous observations of an 11.2 GHz satellite beacon with a 5.8° elevation angle in Austin, Texas are presented and compared to CCIR predictions.**

INTRODUCTION

Systematic measurements of satellite beacon rain attenuation have been carried out since late 1960s in the US, Europe, and Japan. Their results have been used to develop and verify the many prediction methods now in worldwide use, of which the CCIR and Global models may be the most familiar. These models predict the annual cumulative probability of exceeding a given fade on a specific satellite link, taking into account such parameters as the ground location, the frequency, and the elevation angle.

The prediction models have reached a reasonable state of maturity and perform with adequate average accuracy on links with non-extreme conditions, i.e., for elevation angles above about 30° and in temperate climate zones. The modeling interest, therefore, has shifted towards trying to forecast the year-to-year variability of fading, using approaches such as *Worst Month* predictions and other statistical approaches.

Characterizing the natural variability, return period, or prediction risk associated with rain attenuation requires data obtained over a sufficiently long period of time [1]. Most of the data sets available in the CCIR data base, the official repository for beacon fade data, however, do not exceed 2 to 3 years and this is not adequate to test variability model designs. As a remedy, the 11.2 GHz beacon observations in progress in Austin, Texas, since June 1988, are being continued [2] and this paper summarizes some of the results from the first 5 years of the experiment.

EXPERIMENTAL DETAILS

Data Collection

The experimental equipment for the measurements at Austin, Texas (30.39°N lat., 97.73°W long., 185 m alt., CCIR Climate Region M), incorporates a 2.4 m diameter receiving antenna feeding both a beacon receiver and a radiometer, a tipping bucket rain gauge, and sensors for wind, relative humidity, and pressure. Employing a single antenna ensures the alignment of the volume from which the thermal radiation emanates with the path of the beacon signal. Its measured sky coupling efficiency, h, is 0.98. A block diagram of the receiving equipment is shown in Figure 1.

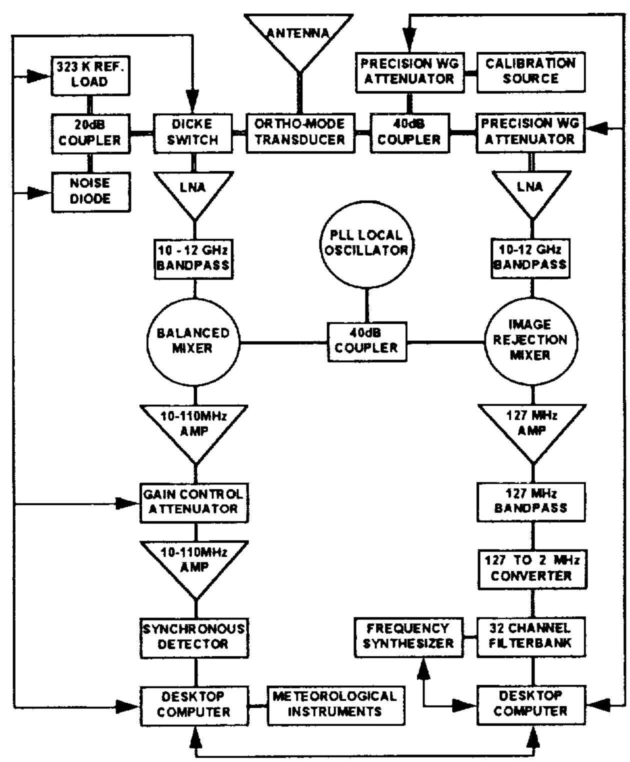

Fig. 1 11.2 GHz Beacon Receiver and Radiometer Block Diagram.

The data reported pertain to the five-year period from June 1988 to May 1993, during which the right-hand circularly polarized (RHCP) 11.198 GHz signal from a succession of three INTELSAT geostationary satellites located at 335.5°E was monitored, with a path elevation angle of 5.8°. Salient features of the beacon receiver are a K_u-Band low-noise amplifier and a 32 channel frequency-

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tracking filter bank with 100 Hz bandwidth (BW) and a 0.9 Hz post detection BW, resulting in a fade margin of 25 dB. The receiver output is sampled at a 2 Hz rate. The radiometer implements a gain controlled, continuously self-calibrating Dicke-switched design with a total noise BW of 200 MHz centered at 11.325 GHz (LHCP), a 1 s integration time, and a sensitivity of less than 0.1 K. The radiometer and meteorological sensors are sampled at a 0.1 Hz rate; rain gauge tipping times are recorded asynchronously with a resolution of 0.06 s. Both experiment control and data acquisition are personal computer driven.

Beacon receiver calibrations were performed approximately quarterly by the signal injection method to allow for the characterization of the receiver in the enhancement region and to avoid having to rely on rare periods with low scintillations for a constant reference signal. The calibrations verified that receiver gain changes were negligible. The radiometer noise diode was calibrated against liquid nitrogen at the beginning of the experiment and diode aging appears to be insignificant, as the lowest sky temperature observed during dry winter nights repeated from year to year.

Data loss through equipment malfunction was minimized by careful system design, built-in redundancy, and daily operator inspection. During the five year period only one failure occurred during a fade event, but the data could be recovered from simultaneous strip-chart recordings. Data gaps caused by calibration or maintenance are judged to have negligible impact on the statistical results.

Data Processing

Calibration verified both constant gain and linearity of the receiver, but several factors contribute to a time varying offset. These need to be separated by post-acquisition data processing to derive the level of the received signal with respect to free space or clear air. The radiometer derived attenuation for non-rain fade periods is the most important ingredient in this procedure.

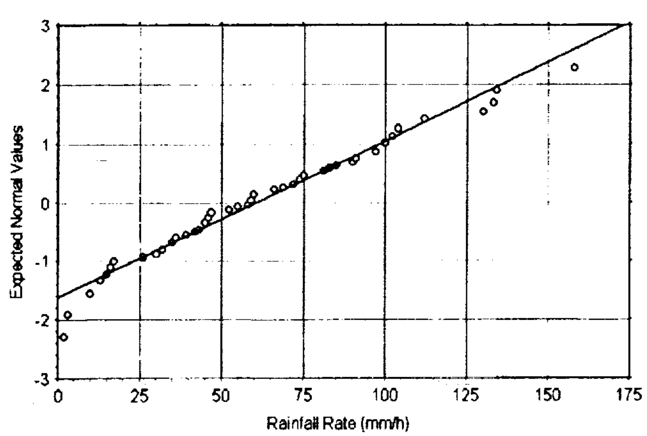

Fig.2 The 0.01% Rainfall Rate for the 60 Month Measurement Period Indicates Normal Behavior.

At the low elevation angle of this experiment, scintillations of the beacon level (±5 dB at 0.01% of time) were observed nearly always, even during rain fades, as verified by comparing the variations of beacon and radiometer time series. To separate rain fading from scintillation fading it is therefore not sufficient to just extract beacon data for time periods during which the radiometer is above a threshold (e.g., 110 K); the scintillations have to be removed by low-pass filtering of A_{fs} or A_{ca}. For the results presented here, we chose a moving averager window width of 3 min, which rejects about 80% of the scintillation power without causing overshoots after rapidly-decaying rain fades, based upon a graphical inspection of fade events.

RESULTS

Rainfall Rate

The rainfall rate at 0.01% annual probability for CCIR Climate Region M is 62.5 mm/hr, but for the 5-year measurement it averages 73.6 mm/hr, indicating that the CCIR classification does not fully account for Austin's subtropical climate in which rainfall often occurs in very heavy showers. The mean monthly 0.01% rainfall rate over the 60 month measurement period, however, is 60.7 mm/hr. A chi-squared fit performed on the data indicates that the monthly 0.01% rainfall rate is normally distributed with a standard deviation of 36.2 mm/hr, as depicted in Figure 2.

The month-by-month tabulation of the measured rainfall statistics has been included in Appendix A. Cumulative distributions of the rainfall rate observed for each of the 5 years, the overall period, and the *worst month* have been plotted in Figure 3.

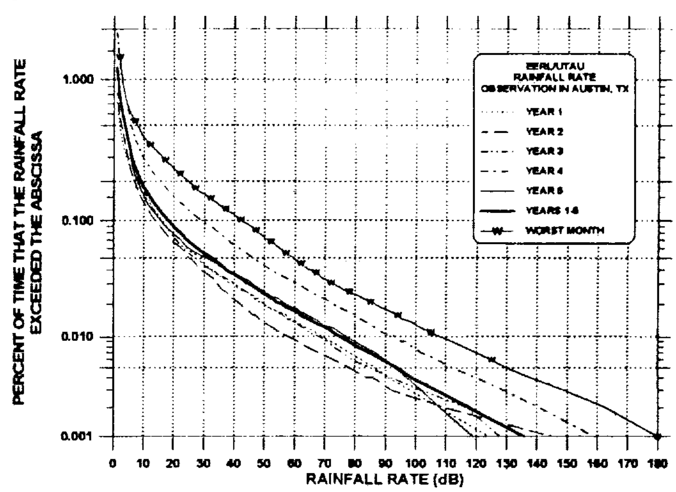

Fig. 3 Cumulative Distributions of the Annual Rainfall Rate for the 5 Years of Observation in Austin, Texas.

Fading

Figure 4 plots the percentage of time that the unfiltered clear air attenuation exceeded the values drawn on the abscissa for each of the 5 observation years, as well as the overall period. Note that the ordinate has a normal probability scale. Fades predicted by the CCIR method as given in Report 564 have also been included and are represented by the symbol C. There are two distinct domains in the graph. Fades less than about 5 dB are dominated by scintillations symptomatic for a low-elevation angle path. As scintillations are present for almost all of the time, year-to-year variations are very small. The higher fades are due to rain attenuation, are relatively rare events, and therefore exhibit much higher year-to-year variability. It is obvious, however, that the CCIR prediction method seriously underestimates rain fading.

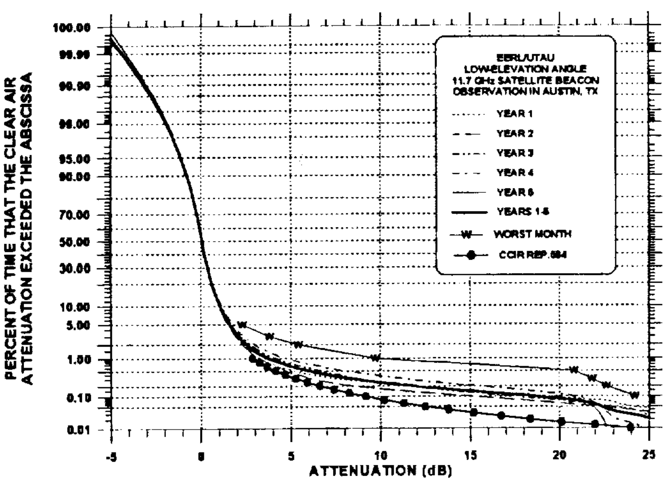

Fig. 4 Annual Cumulative Distributions of 11.2 GHz Rain Fades Measured in Austin, Texas, over a 60 Month Period.

The experiment's dynamic range of less than 25 dB is not adequate to characterize the 0.01% fades. During the *worst month*, 20 dB fades were exceeded for about 1% of the time. The average difference between monthly and 5-year fades exceeded at percentages between 0.1 and 1 has been plotted in Figure 5 along with the standard deviation. The average difference at 0.1% is about -4 dB, i.e., the monthly average 0.1% fade is about 14 dB, as opposed to the annual 0.1% fade value of 18 dB. Common sense would indicate that the average difference ought to be 0 dB. The discrepancy can be blamed on an apple/orange comparison. When comparing cumulative distributions, one has to have the same timebase. As an example, assume a month to have 100 hours and a year to consist of 2 months. During the first month, let fades exceed 5 dB for 1 hour, during the second month, fades exceed 5 dB for 2 hours and 10 dB for 1 hour. Assume fades were 0 dB at all other times. The two 1% fade levels are then 5 dB and 10 dB, with an average of 7.5 dB. The year, consisting of 200 hours, had 197 hours at 0 dB, 3 hours exceeding 5 dB, and 1 hour exceeding 10 dB. At 1% (2-hours), the annual fade exceeded only 5 dB. A table of the monthly and annual rain attenuation in excess of clear air, lowpass filtered with a 180 s window, has been added in Appendix B.

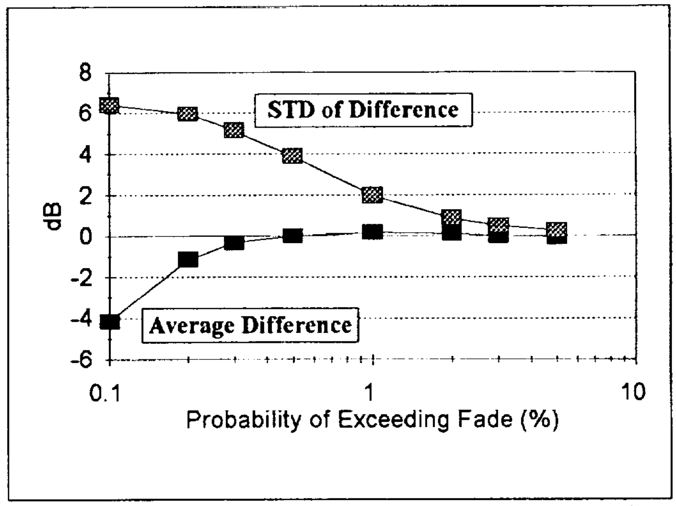

Fig. 5 The Average Difference Between the 5-Year CDF and the 60 Monthly CDFs.

Radiometric Medium Temperature

The 60 monthly values of the radiometric medium temperature, used for converting sky temperature to fades, are normally distributed and have a mean value of 266.7 K and a standard deviation of 5.5 K. Figure 6 shows a time series of the medium temperature estimates. The first 15 months have a lower average than the later months. At this time the cause for this trend is not known, however, it merits further investigation.

Conclusion

Observations of beacon rain fades on an 11.2 GHz path with 5.8° elevation have been performed for 5 years and are still continuing. The value of the long, uninterrupted and homogeneous data set will be for the modeling of the variability of rain fading. The results so far show that the CCIR prediction method consistently underestimates the attenuation due to rain fading on this link.

References

[1] R. K. Crane, "Worst-month rain attenuation statistics: A new approach," *Radio Science*, vol. 26, no. 4, pp. 801-820, 1991.

[2] Vogel, W. J., G. W. Torrence, and J. E. Allnutt, "Rain Fades on Low Elevation Angle Earth-Satellite Paths: Comparative Assessment of the Austin, Texas 11.2 GHz Experiment," (invited), to be published in IEEE Proceedings, June 1993

APPENDIX A: Monthly and Annual Rain Rates (mm/h) Exceeded with Time Percentages from 0.5 to 0.001 in Austin, Texas, During the Five Year Period from June 1988 to May 1993.

Time	Rain Rate at Percentage											
yymm	0.5	0.3	0.2	0.1	0.05	0.03	0.02	0.01	0.005	0.003	0.002	0.001
8806	2	6	12	31	55	70	79	90	99	110	121	126
8807	2	6	13	22	31	36	40	45	47	52	53	55
8808	0	1	2	9	16	27	33	60	81	99	108	111
8809	1	3	4	6	9	12	20	43	51	69	82	87
8810	0	0	2	3	16	25	48	69	81	84	92	96
8811	0	0	0	1	2	5	7	10	20	24	27	32
8812	1	2	3	4	6	8	8	10	12	13	14	15
8901	4	8	11	16	21	25	29	35	41	46	47	50
8902	0	1	2	4	7	9	10	13	15	16	23	24
8903	2	8	12	23	37	47	55	85	136	144	152	172
8904	1	3	8	20	52	74	94	112	132	138	144	151
8905	8	17	24	39	56	64	68	81	98	105	108	129
Year1	1	4	7	15	28	39	49	70	88	101	111	137
8906	1	4	6	15	25	34	40	59	78	84	87	94
8907	0	0	0	0	0	0	0	3	7	7	8	16
8908	4	9	15	27	38	43	50	66	96	111	115	140
8909	0	0	0	1	9	14	17	32	69	74	76	77
8910	3	4	4	7	13	17	19	26	44	56	57	61
8911	2	2	3	5	6	9	11	17	21	22	28	30
8912	0	0	0	0	1	1	2	2	3	3	3	4
9001	1	1	2	3	7	11	13	16	21	22	28	29
9002	5	7	11	18	28	35	39	46	53	58	65	66
9003	4	6	8	12	18	24	28	30	35	36	38	39
9004	4	6	7	15	27	36	47	98	182	194	199	199
9005	10	21	31	47	67	82	96	134	180	199	199	199
Year2	2	4	6	13	24	34	42	59	79	97	125	173
9006	0	0	1	11	53	80	105	130	159	172	178	194
9007	4	5	8	15	27	39	50	59	69	72	73	75
9008	0	0	0	0	3	5	7	10	14	18	19	21
9009	2	4	8	20	41	54	69	75	84	95	102	130
9010	5	7	9	14	20	31	36	58	75	82	87	89
9011	4	7	9	13	21	27	32	47	51	57	61	68
9012	0	1	1	7	19	26	31	46	70	76	82	94
9101	9	12	16	21	29	37	42	47	55	57	60	66
9102	5	6	7	9	17	29	32	44	62	65	75	77
9103	0	1	2	3	7	12	17	42	58	71	75	77
9104	3	5	7	11	30	49	65	91	117	129	133	153
9105	3	12	19	32	50	61	72	100	115	124	127	139
Year3	3	6	8	15	26	40	50	68	86	109	118	140
9106	3	6	10	22	34	43	56	74	98	121	150	170
9107	0	1	4	8	31	46	60	83	92	95	98	105
9108	8	17	25	42	88	114	128	158	193	193	199	199
9109	1	5	12	25	37	44	48	60	71	80	83	98
9110	1	7	15	33	62	77	89	104	135	147	150	167
9111	0	1	4	11	20	30	35	45	52	63	64	65
9112	17	24	33	49	67	78	83	91	100	101	103	110
9201	4	5	5	7	8	9	12	15	18	19	19	20
9202	7	8	11	19	34	43	52	60	75	88	108	121
9203	6	10	16	28	45	57	65	75	84	88	99	110
9204	3	4	5	7	13	21	38	52	63	99	106	112
9205	12	22	35	54	72	90	102	133	156	168	177	186
Year4	5	9	15	28	46	61	73	93	115	134	147	171
9206	3	6	12	27	46	65	82	97	105	111	113	117
9207	0	2	2	3	6	7	11	16	20	21	21	28
9208	0	2	4	11	15	19	26	39	48	50	52	56
9209	3	5	9	41	68	83	92	100	110	116	120	127
9210	0	0	0	13	31	42	54	73	88	96	107	120
9211	6	10	14	37	61	75	85	104	131	143	150	174
9212	4	6	8	12	19	23	27	33	45	49	53	55
9301	5	6	8	10	16	22	24	36	44	50	55	62
9302	4	6	7	12	17	22	25	35	44	59	84	96
9303	2	5	8	15	23	33	44	55	62	67	80	87
9304	4	6	10	18	27	42	57	72	79	83	86	92
9305	5	7	10	28	47	56	77	102	119	128	135	140
Year5	3	5	7	15	30	46	57	78	94	104	111	127
Yrs1-5	3	6	9	18	32	45	56	75	95	111	125	148

APPENDIX B: Monthly and Annual Rain Attenuation (dB) in Excess of Clear Air (50% @ 0dB) Measured in Austin, Texas, at a Frequency of 11.2 GHz with an 5.8° Elevation Angle. The Fade Margin of the System was Nearly 25 dB. The Data have been Low-Pass Filtered with a 180 s Window.

Time	Attenuation at Percentage															
yymm	5	3	2	1	0.5	0.3	0.2	0.1	0.05	0.03	0.02	0.01	0.005	0.003	0.002	0.001
8806	0.8	1.1	1.6	3.5	8.4	15.6	20.1	23.1								
8807	1.0	1.4	1.8	3.1	5.2	7.5	10.3	17.9	23.1							
8808	1.0	1.2	1.5	2.7	5.1	7.1	10.8	16.6	21.3	23.8						
8809	1.0	1.3	1.6	2.8	5.8	9.0	13.5	17.3	20.8	23.2						
8810	0.6	0.7	0.9	1.2	1.8	3.0	4.8	8.4	13.0	22.3						
8811	0.6	0.7	0.8	1.0	1.4	1.8	2.4	4.5	10.1	14.9	16.7	18.2	20.5	21.2	21.5	21.7
8812	0.8	1.0	1.2	1.5	2.1	2.6	2.8	3.0	3.4	3.6	3.7	4.0	5.9	6.4	6.6	6.7
8901	1.0	1.3	1.7	2.8	4.2	5.9	8.1	12.6	16.6	20.3						
8902	0.7	0.8	0.9	1.1	1.3	1.6	2.0	2.8	6.1	9.0	10.2	11.5	13.1	13.8	14.1	14.3
8903	0.8	1.1	1.7	3.7	6.1	8.4	10.7	16.9	20.4	22.2	23.1					
8904	0.8	1.1	1.3	2.0	4.6	7.4	9.5	16.3	22.7							
8905	0.8	1.3	2.1	8.6	18.6											
Year1	0.9	1.1	1.4	2.4	4.8	7.7	11.6	18.9	23.5							
8906	0.9	1.3	1.9	4.0	6.1	10.2	21.5									
8907	0.8	1.0	1.2	1.6	2.5	4.0	6.4	12.2	15.2	16.6	17.7					
8908	1.0	1.2	1.5	2.3	4.6	7.0	10.4	16.5	20.8							
8909	0.9	1.1	1.2	1.5	1.9	2.4	3.7	6.1	10.9	16.2	17.5	21.4				
8910	0.8	1.1	1.3	2.6	5.2	6.2	7.1	15.2	23.9							
8911	0.7	0.9	1.1	1.6	3.0	4.1	4.9	6.1	7.3	7.8	8.4	9.9	10.6	10.8	10.8	10.9
8912	0.5	0.6	0.6	0.8	0.9	1.0	1.2	1.4	1.5	1.6	1.6	1.7	1.7	1.7	1.8	1.8
9001	0.8	1.0	1.2	1.4	1.7	2.0	2.2	2.8	3.6	4.0	4.3	5.1	8.9	9.6	9.9	10.1
9002	0.9	1.4	2.2	3.8	5.6	8.1	11.1	15.1	17.3	19.1	20.8	21.5	22.1	22.6	22.9	23.0
9003	0.8	1.1	1.3	2.1	4.3	5.4	6.1	7.0	8.1	9.6	12.0	14.6	17.2	18.2	18.5	18.8
9004	0.7	1.0	1.4	4.5	6.6	9.7	12.3	22.3								
9005	0.8	1.1	1.6	4.0	11.9	16.9	19.5	23.8								
Year2	0.9	1.1	1.4	2.3	4.4	6.1	8.2	15.1	21.7							
9006	0.7	0.8	1.0	1.2	1.7	2.3	3.9	13.9	20.3	23.2	23.7	24.2				
9007	1.2	1.8	2.6	4.1	6.6	9.6	11.8	15.2	18.8	20.3	21.6	22.8	23.4			
9008	0.9	1.2	1.4	1.9	2.7	4.3	7.1	12.2	19.0	22.2	24.0	24.1				
9009	1.2	1.6	2.2	4.0	5.5	7.4	9.1	12.4	15.7	19.8	21.8	23.2	24.0			
9010	0.9	1.1	1.5	4.1	6.7	9.0	11.8	21.9	24.3							
9011	0.8	1.2	1.7	3.4	5.5	6.7	8.3	16.9	22.4	23.8	24.3					
9012	0.7	0.9	1.0	1.3	1.6	1.9	2.3	3.3	4.6	5.6	6.2	7.7	8.2	8.7	8.8	8.9
9101	1.4	2.7	4.1	7.5	10.0	12.1	13.7	16.1	19.3	20.5	21.3	23.9	24.3			
9102	0.7	1.0	1.3	2.9	8.3	10.2	11.6	14.2	17.2	19.1	23.1	24.3				
9103	0.7	0.9	1.2	2.0	3.1	4.2	5.4	9.1	11.5	13.3	14.6	15.5	15.8	16.6	16.9	17.0
9104	1.0	2.2	3.9	6.5	9.6	17.6	22.6	24.2								
9105	1.0	1.5	2.2	4.6	8.8	14.7	18.9	22.9	24.1							
Year3	1.0	1.3	1.8	3.7	6.5	8.9	11.2	17.0	22.4	24.2						
9106	1.0	1.6	2.3	4.1	6.4	10.2	12.3	18.5	24.0							
9107	0.9	1.2	1.6	2.7	6.0	9.9	12.1	15.7	18.1	19.2	19.9	20.4				
9108	1.1	1.6	2.3	4.7	10.7	15.7	19.6	23.1	24.0							
9109	1.3	1.7	2.3	3.9	6.0	8.1	9.6	11.7	16.2	19.6	20.7	23.9				
9110	0.9	1.3	1.8	4.6	11.0	15.0	17.9	20.5	21.4	22.0	22.2	22.4				
9111	0.8	1.0	1.1	1.4	1.9	2.4	3.3	9.1	13.1	18.7	21.0	22.4	22.7			
9112	2.3	3.8	5.4	8.9	12.5	17.0	19.3	21.6	22.1	22.2	22.2					
9201	1.1	1.4	1.6	2.3	3.1	3.7	4.1	4.6	5.1	5.7	5.9	6.3	7.8	8.4	8.8	9.0
9202	1.6	2.2	2.8	4.8	7.4	8.7	9.8	11.2	15.1	23.0	23.1					
9203	0.9	1.4	2.8	5.3	8.4	11.7	14.5	18.5	21.2	22.1	22.5					
9204	0.7	1.1	1.7	3.5	5.3	6.5	7.1	8.3	9.4	10.4	10.8	12.6	15.7	16.6	16.8	17.0
9205	1.4	1.4	3.9	9.7	20.8	21.8	22.0	22.4	22.6	22.7	22.8	23.0				
Year4	1.2	1.7	2.4	4.5	7.9	11.5	14.9	20.5	22.1	22.5	22.9	24.2				
9206	1.0	1.7	2.7	6.1	11.2	20.9	22.2	22.6								
9207	0.8	1.0	1.2	1.5	2.1	2.9	4.0	5.4	8.7	10.2	11.7	14.9	15.8	16.1	16.2	16.3
9208	0.9	1.3	1.6	2.9	5.5	8.4	10.1	14.9	21.7							
9209	0.9	1.1	1.5	3.7	7.4	14.1	18.4	21.5	22.0	22.3						
9210	0.7	0.8	1.0	1.3	2.2	4.4	11.8	20.0	22.0							
9211	1.0	1.7	2.7	5.6	8.9	11.2	13.2	16.9	18.8	20.7	21.3	22.2				
9212	0.9	1.2	1.6	2.6	3.5	5.0	6.3	7.6	8.5	9.2	9.8	11.8	14.6	15.2	15.4	15.7
9301	0.9	1.1	1.4	2.4	4.4	6.0	7.5	12.2	14.9	16.3	18.2	19.7	21.0	21.5	21.8	22.0
9302	0.9	1.2	1.6	2.6	3.9	5.4	6.4	9.1	12.3	15.8	17.3	21.2	21.8			
9303	0.9	1.2	1.5	2.0	3.2	5.1	7.0	9.9	13.8	17.9	19.9	22.1				
9304	0.9	1.1	1.5	3.1	5.4	7.5	10.3	17.6	21.6	22.0						
9305	1.0	2.0	3.5	5.8	8.8	15.2	19.0	21.2	21.8							
Year5	0.9	1.2	1.6	3.1	5.7	8.4	11.1	18.2	21.8	22.1	22.3	22.7				
Yrs1-5	1.0	1.3	1.7	3.2	5.9	8.7	11.7	18.4	22.1	23.3	24.3					