Channel quality variation and its impact on data link protocol performance

David Arcoraci
Harris Corporation,
RF Communications Division

Presentation overview

- Overview of channel quality variation
- Measuring channel quality variation
- Statistical model of channel quality variation
- Incorporating the channel variation model into an HF channel simulator
- Data link protocol performance measurements under simulated channel quality variation

Presentation summarizes work to be reported in two forthcoming papers:

- William M. Batts, Jr., William N. Furman, and Eric N. Koski, “Empirically Characterizing Channel Quality Variation on HF Ionospheric Channels”, Nordic Shortwave Conference 2007 (HF 07), August 14-16 2007, Fårö, Sweden.
- Batts, Furman, Koski, “Channel Quality Variation as a Design Consideration for Wireless Data Link Protocols”, submitted to IEEE Military Communications Conference MILCOM 2007, October 29-31 2007, Orlando, Florida, USA.

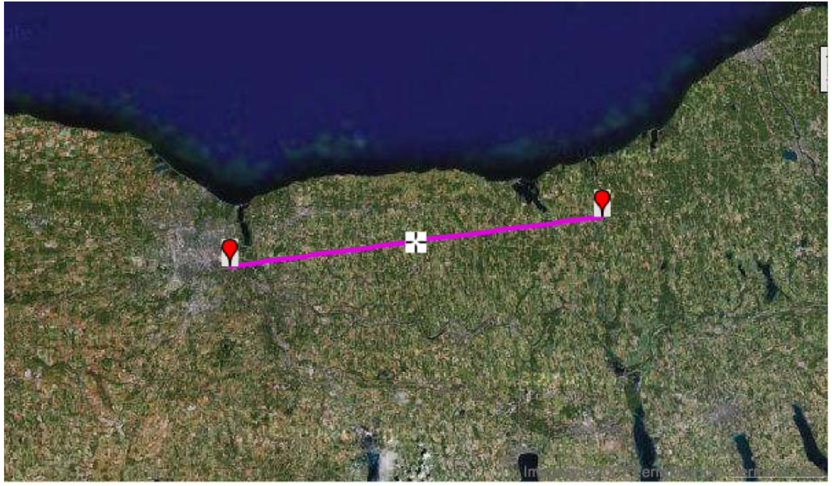
Channel quality variation

- Performance of HF communications techniques is typically measured under a standard set of simulated HF channel conditions as specified by ITU-R Rec. F.1487 (per the 'Watterson' HF channel model)
- Most commonly used:
  - Gaussian noise
  - ITU-R 'Mid-Latitude Disturbed' channel profile: two paths, 2 ms multipath spread, 1 Hz Doppler spread
- HF ionospheric channel conditions vary constantly over time scales of seconds to minutes; this variation is not captured by the 'Watterson model' or by ITU-R Rec. F.1487
- Hypotheses:
  - This 'medium-term' variation could have a significant impact on HF communications system performance, especially that of adaptive communications techniques
  - The *incremental redundancy* techniques used in HDL+ are especially likely to have beneficial impacts under conditions of 'medium-term' channel variation
- Precedents:
  - Furman&McRae paper, MILCOM 1993
  - Recent papers by Eric Johnson using 'Walnut Street' model

Characterizing channel quality variation

- Collected time-series (60 to 72 hours) of channel SNR readings using S4538 BW5 at intervals of 2.7 seconds
- To remove diurnal variation component, high-pass filtered with 5th-order Chebyshev filter, f_c = 0.001 Hz (16.67 min.)
- Computed 2048-point FFTs (~90 minutes) started at each hour in the time series, to characterize ‘variation spectrum’
- Re-filtered with second filter, f_c = 0.01 Hz, and computed before-and-after variances to separate into ‘Long-Term Variation’ (LTV) vs. ‘Intermediate-Term Variation’ (ITV)
- Sampling interval determines Nyquist frequency of 0.185 Hz. Rayleigh fading (per Watterson model) results predominantly in variation above the Nyquist frequency – aliased roughly uniformly across the band
  - 6.3 dB^2 of SNR variance attributed to ‘Rayleigh fading’
- Aggregated variance and spectrum from same time of day to yield 24-hour profile
- Averaged variance and spectrum across the 24 hours to yield 24-hour composite variance and variation spectrum

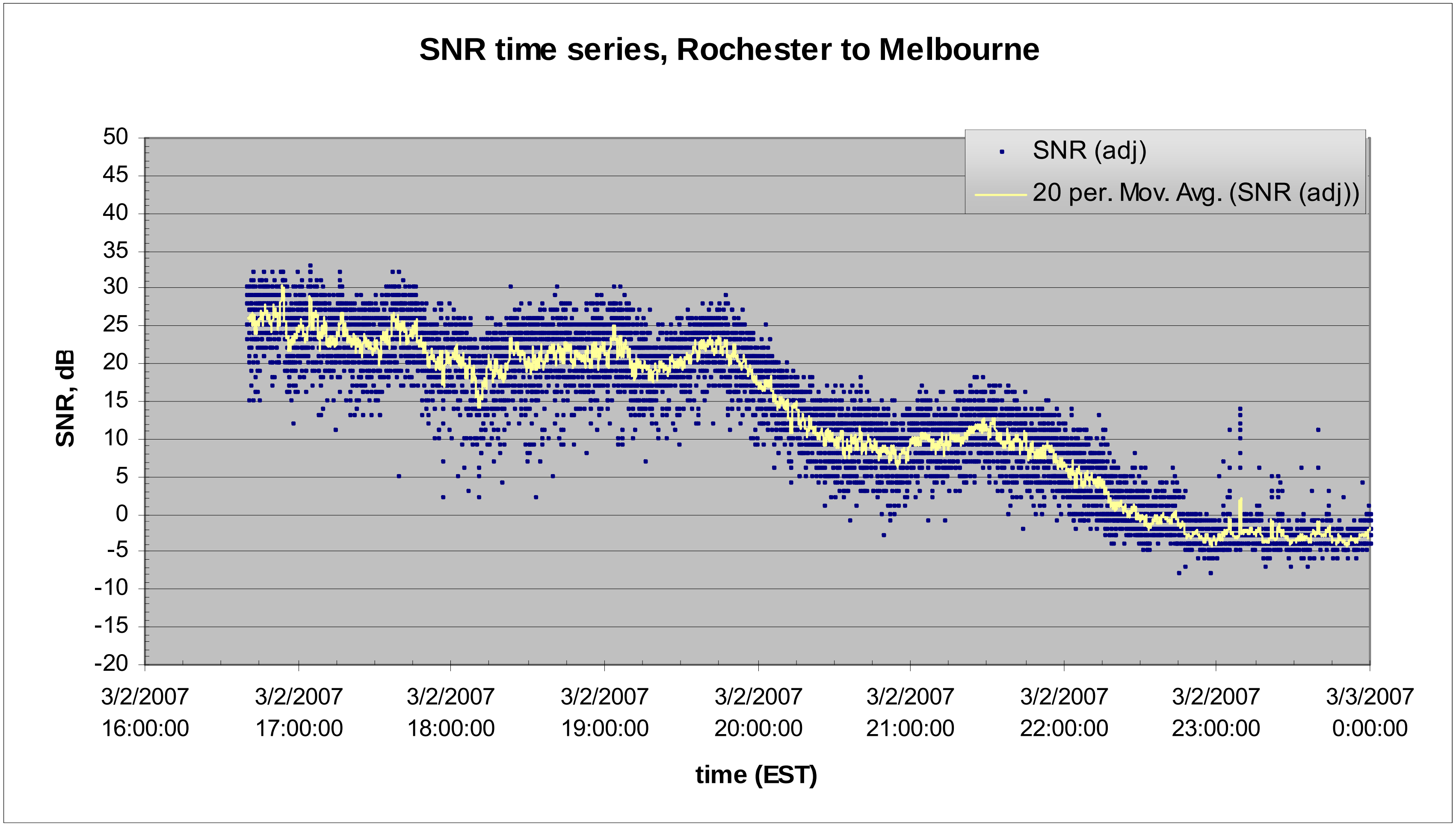
Links used for SNR time-series collection



- 150W Tx power, broadband dipole antennas

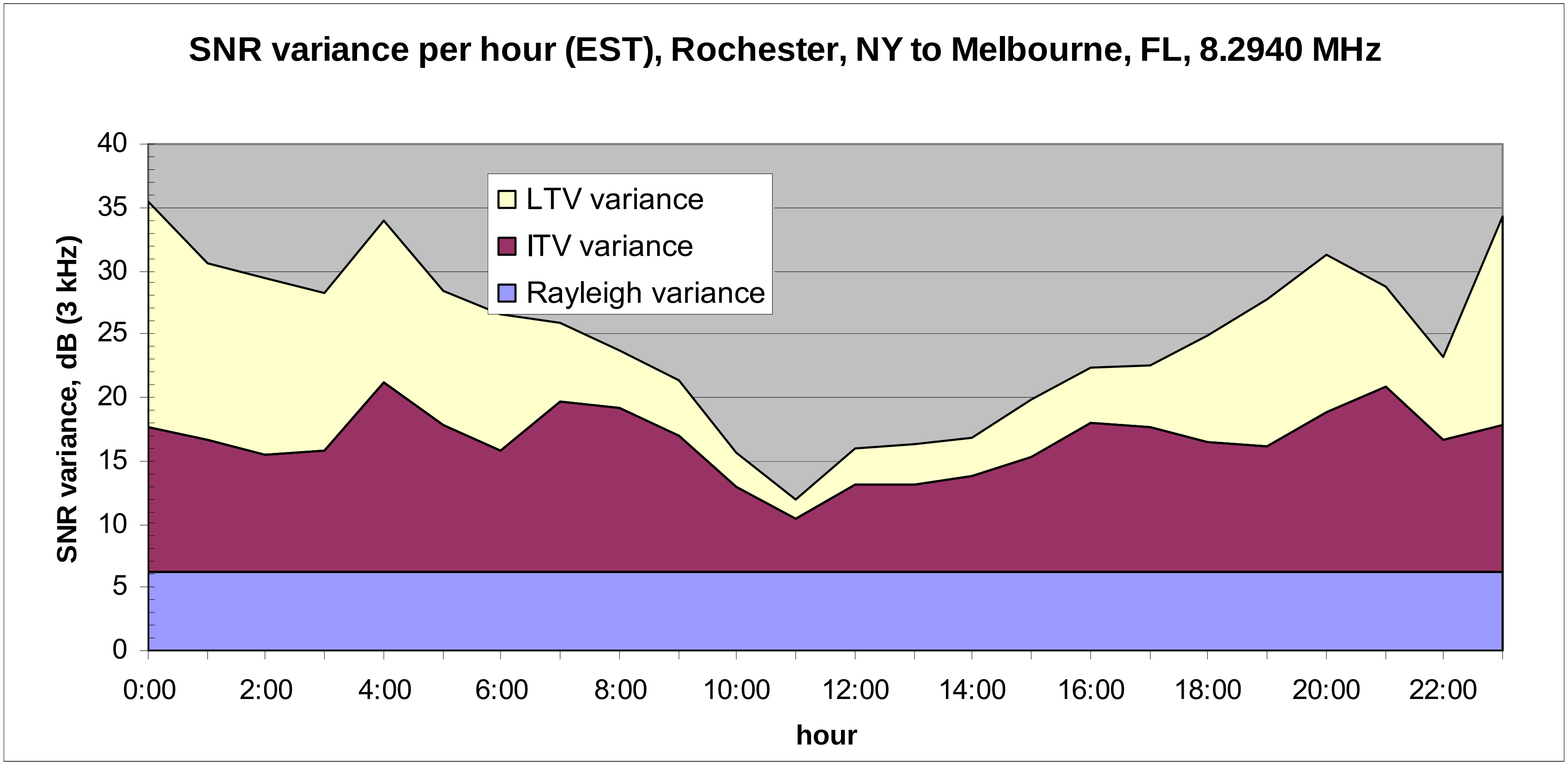
data set	link type	start	end	Tx site	Rx site	distance	frequency
Melbourne 070223	long-haul skywave	2/23/2007 13:14 EST	2/26/2007 15:57 EST	Rochester, NY	Palm Bay, FL	1697 km	8.2940 MHz
Wolcott 070302	NVIS	3/2/2007 16:39 EST	3/5/2007 8:10 EST	Rochester, NY	Wolcott, NY	61 km	6.2300 MHz

SNR time series (example)



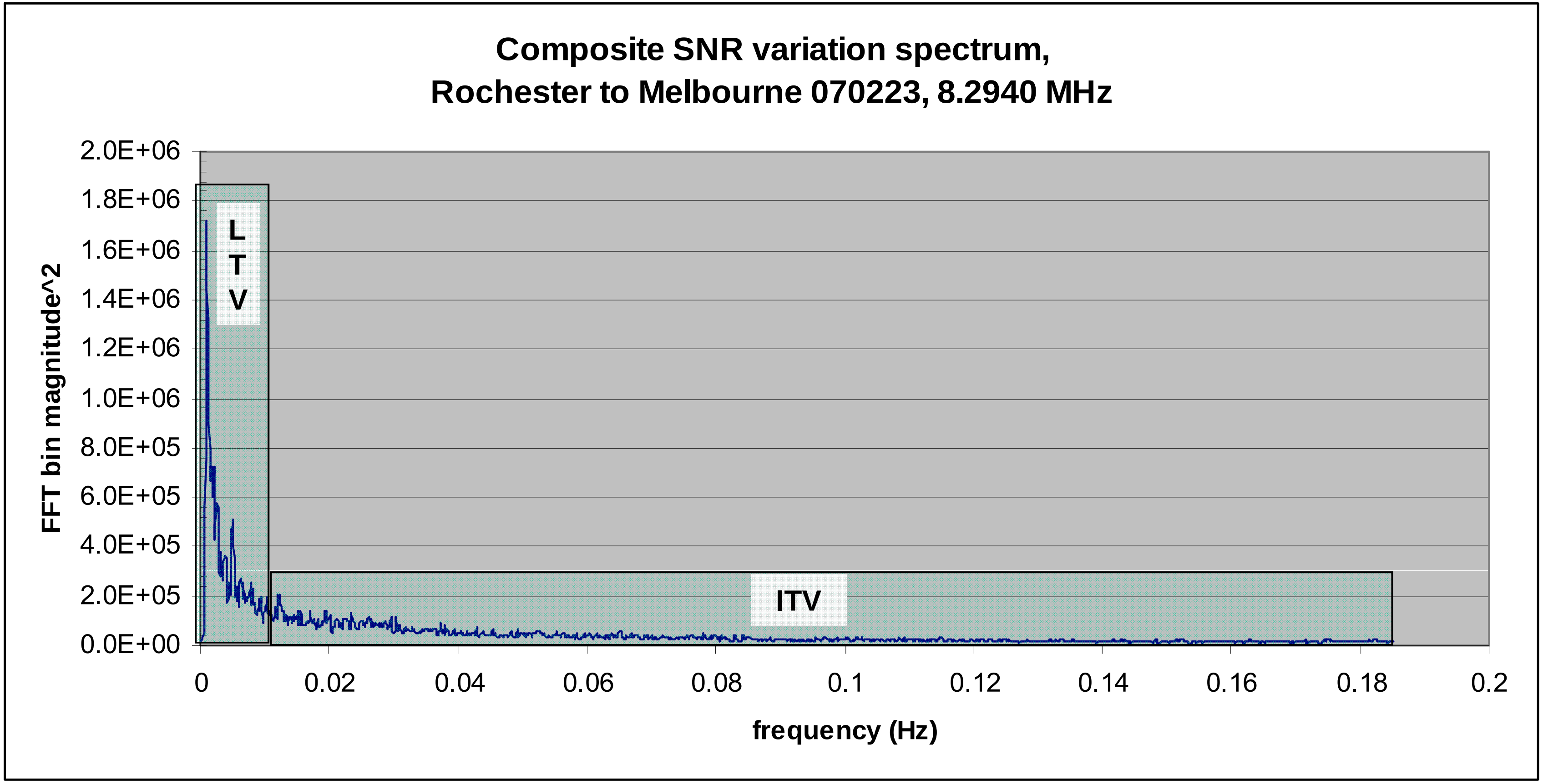
- Each blue dot represents a single SNR observation
- Yellow line averages SNR observations over 54-second interval

SNR variance profile



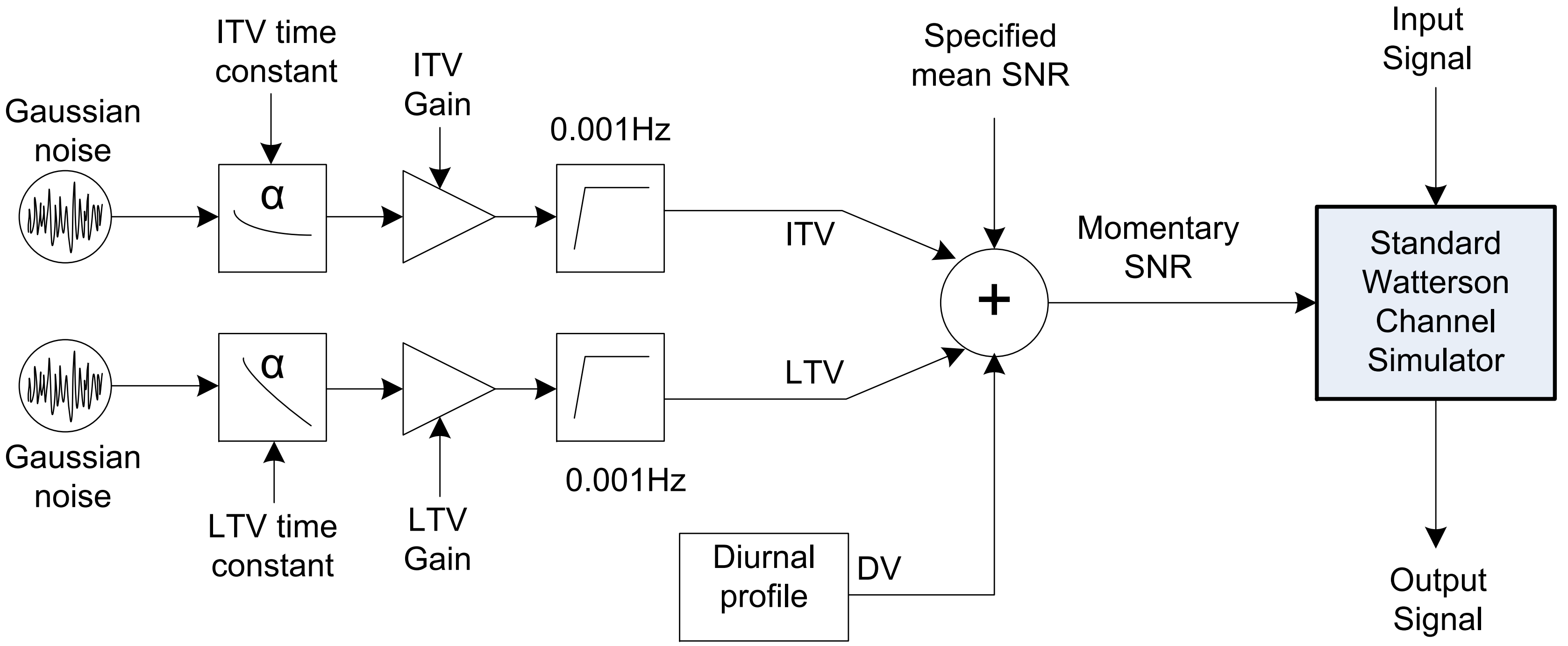
- 6.3 dB^2 of variance attributed to 'Rayleigh fading' per ITU-R MLD model
- Variance is greatest near midnight and day⇔night transitions, least near midday

Composite SNR variation spectrum



- The SNR variation visible in the FFT magnitudes includes two distinct phenomena:
  - 'Long-term variation' (LTV) concentrated below 0.01 Hz
  - 'Intermediate-term variation' (ITV) exhibiting smoothly diminishing magnitude from 0.01 Hz to 0.185 Hz
- 'Rayleigh fading' above 0.185 Hz is aliased uniformly across the band

Channel variation model



- Mean SNR input to Watterson-model simulator is replaced with a momentary SNR parameter reflecting channel quality variation
- Independent generator structures are used to generate Intermediate-Term (ITV) and Long-Term (LTV) random processes
- ‘Alpha filter’ produces noise with exponential autocorrelation
- High-pass filter eliminates variation in the frequency range attributed to diurnal and longer-term processes
- Diurnal profile could be based on measurements or VOACAP/ICEPAC predictions (as in ‘Walnut Street’)

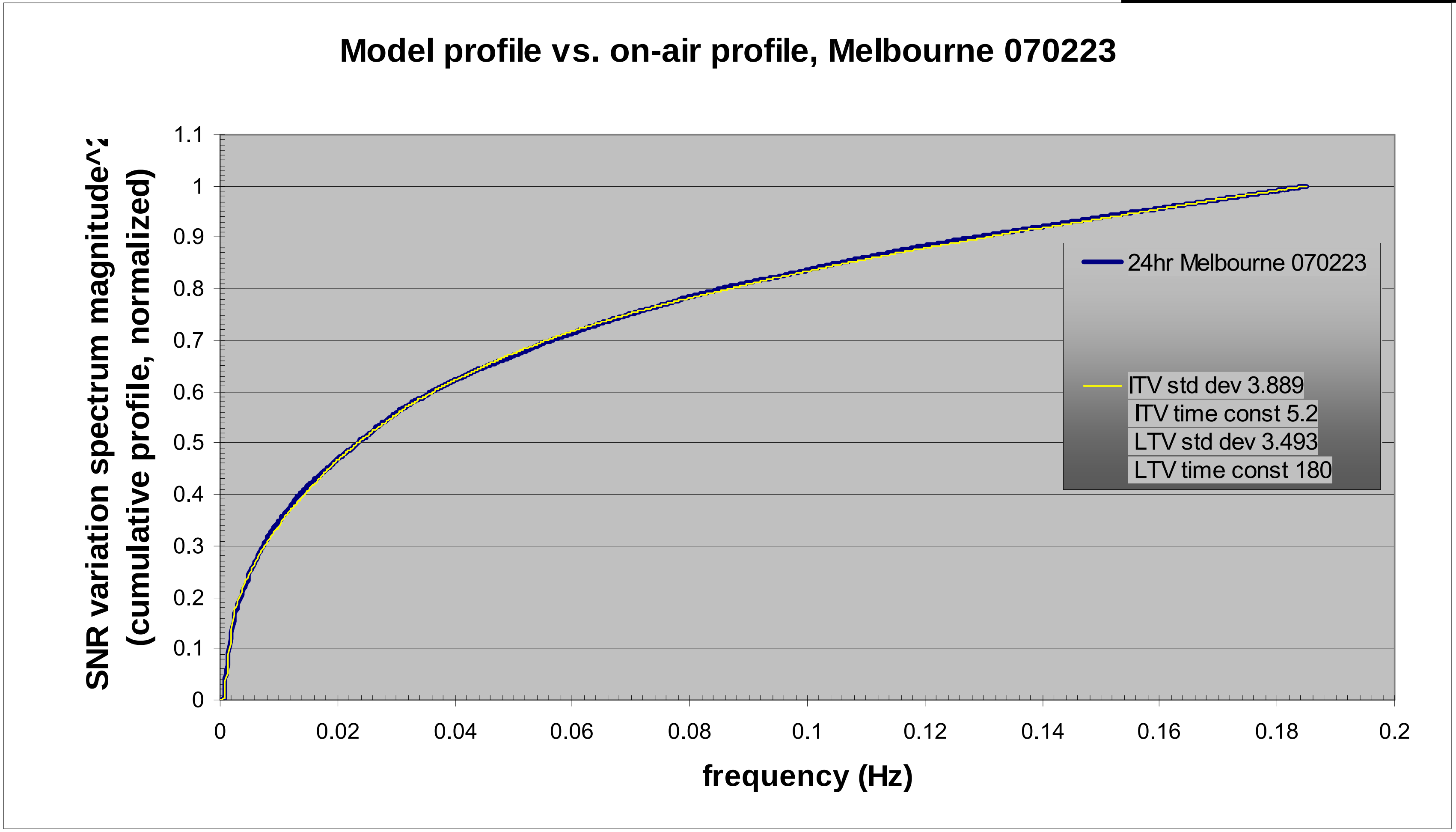
Model calibration

- Basic idea: Specify ITV and LTV parameter-values (gain and time constant) so as to approximate the SNR variation spectrum of a measured data set
- FFT magnitudes are ‘noisy’: exhibit considerable random variation from one bin to the next
- Compute ‘cumulative profile’ from FFT magnitudes to suppress noisy variation
- Use cumulative profiles for calibration

Procedure:

1. Collect on-air time series of SNR observations
2. Compute 24-hour composite SNR variance and variance spectrum (FFT)
3. Repeat
   a. Select candidate ITV and LTV parameters
   b. Generate model SNR time series
   c. Compute time series variance and spectrum
   d. Compare time series and spectra between data set and model
4. Until variance and spectrum ‘match’ sufficiently

Model calibration: cumulative spectral profile

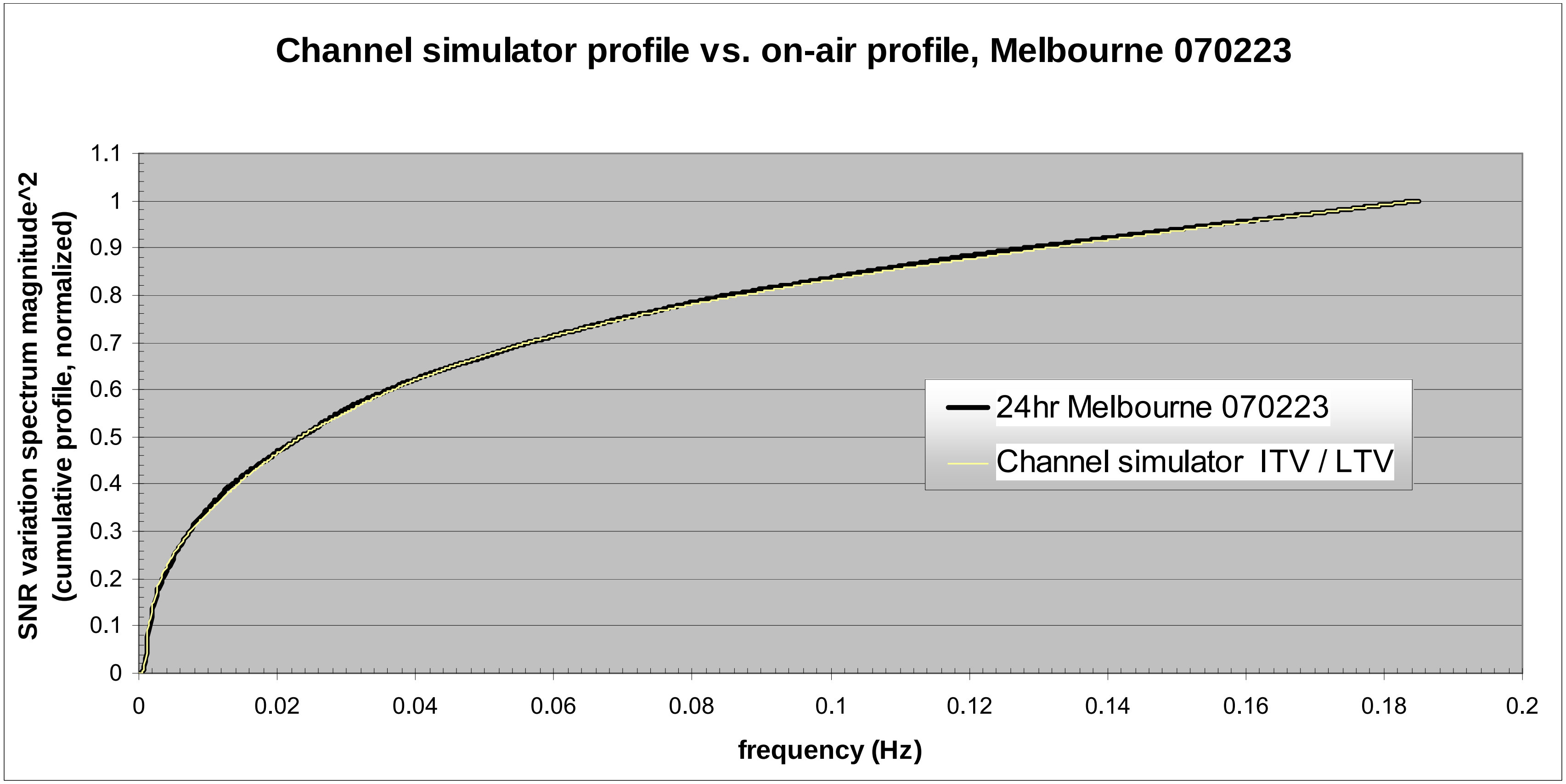


- A PC-based simulation of LTV and ITV processes (together with Watterson-model Rayleigh fading) was used to generate the model profile shown.

Model validation

- Channel variation model incorporated into PC-based ‘Watterson’-model channel simulator (derived from NATO-approved DSP-based simulator)
- ITU-R ‘Mid-Latitude Disturbed’ channel model used to simulate ‘Rayleigh fading’ (similar to fading and multipath observed on the channel)
- Channel variation model uses ITV and LTV parameters obtained by calibrating the model to the on-air data set
- BW5 LQA Sound bursts transmitted radio-to-radio through channel simulator
- Recorded SNR observations on BW5s received over the ‘simulated channel’ (as we did in on-air measurements)
- Computed SNR variance and variation spectrum cumulative profile on observed SNR time series (as with on-air data set)

Simulation model validation



- Model embedded in channel simulator with Melbourne 070223 parameters
- Collected 24-hour time series of SNR measurements, sounding between radios through channel simulator
- Computed FFTs and cumulative spectral profile
- SNR variance 24.6 dB vs. 24.8 dB
- Cumulative profile standard error < 1.0%

Using the calibrated model

- Objective: compare throughput performance of
  - STANAG 5066
  - The new ‘HDL+’ data link protocol proposed for incorporation into STANAG 4538

  under conditions of simulated channel quality variation.
- Hypothesis: HDL+ will cope better with channel quality variation due to its use of *incremental-redundancy* (“Type II Hybrid-ARQ”) techniques
- Procedure:
  - Use PC-based channel simulator with ITV/LTV model to add simulated channel SNR variation to forward and reverse channels
  - Measure delivery time (throughput) for S5066 and HDL+ delivering 100 kbyte (or 50 kbyte) messages under specified conditions

Compare HDL+ vs. S5066 throughput performance, +20 dB

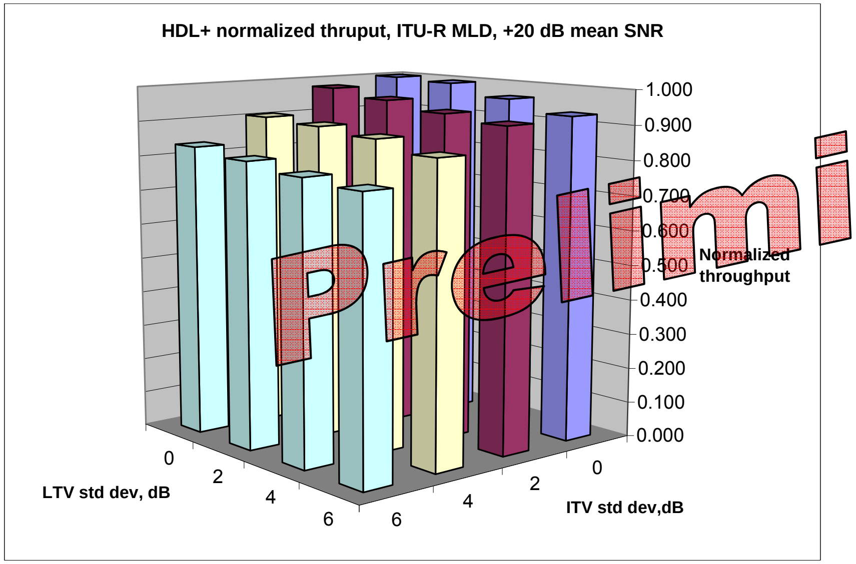
Throughput performance on channels with time-varying SNR, 100 kByte messages

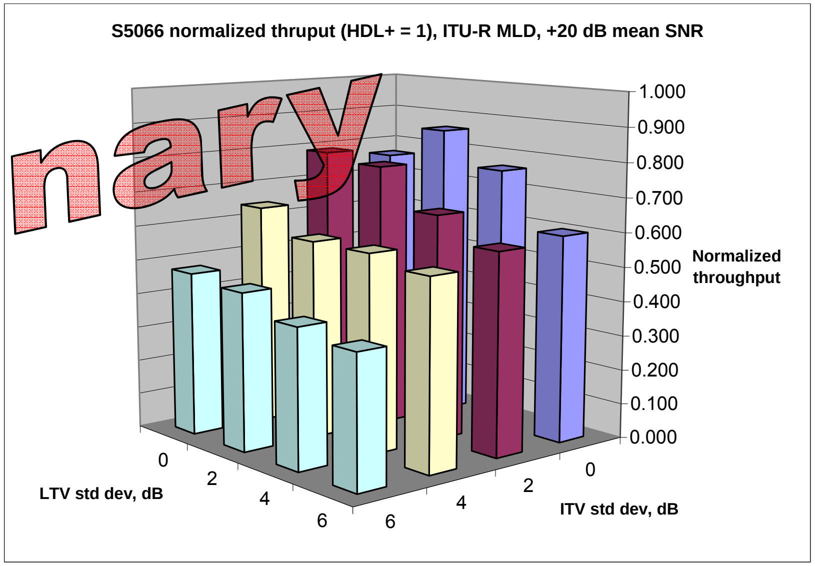
HDL+

		LTV			
		0	2	4	6
ITV	0	1.000	0.995	0.962	0.930
	2	0.978	0.957	0.935	0.919
	4	0.905	0.896	0.880	0.851
	6	0.835	0.816	0.796	0.785

STANAG 5066

		LTV			
		0	2	4	6
ITV	0	0.763	0.858	0.761	0.599
	2	0.789	0.768	0.654	0.583
	4	0.643	0.573	0.572	0.544
	6	0.474	0.456	0.401	0.377


HDL+ normalized thruput, ITU-R MLD, +20 dB mean SNR


S5066 normalized thruput (HDL+ = 1), ITU-R MLD, +20 dB mean SNR

- Data are ‘noisy’ due to modest quantity
- S5066 throughput ~20% worse
- For ITV, LTV std dev = 6 dB, S5066 throughput falls to less than half that of HDL+
- S5066 is clearly much less tolerant of SNR variation

Compare HDL+ vs. S5066 throughput performance, +10 dB

Throughput performance on channels with time-varying SNR, +10 dB mean SNR, 50 kByte messages

HDL+

LTV

ITV

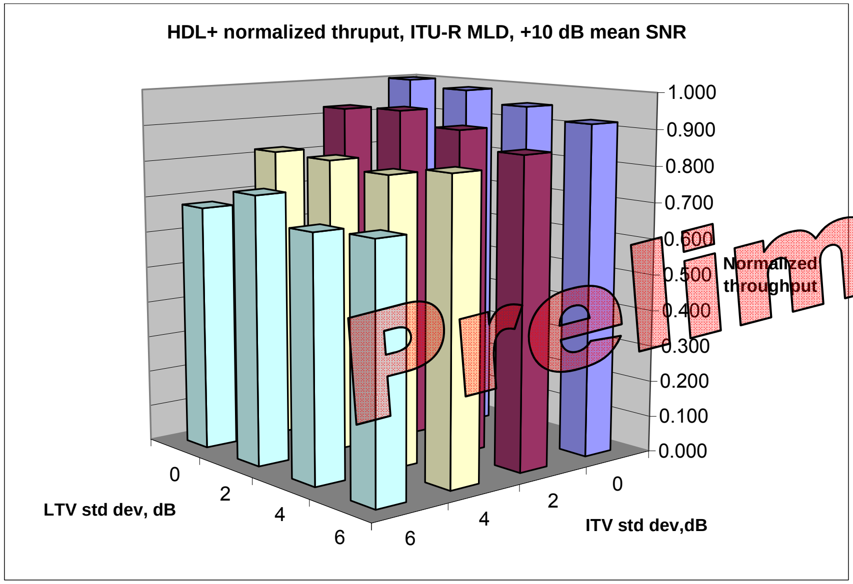
	0	2	4	6
0	1.000	0.983	0.951	0.920
2	0.927	0.937	0.901	0.855
4	0.818	0.815	0.799	0.826
6	0.680	0.741	0.672	0.686

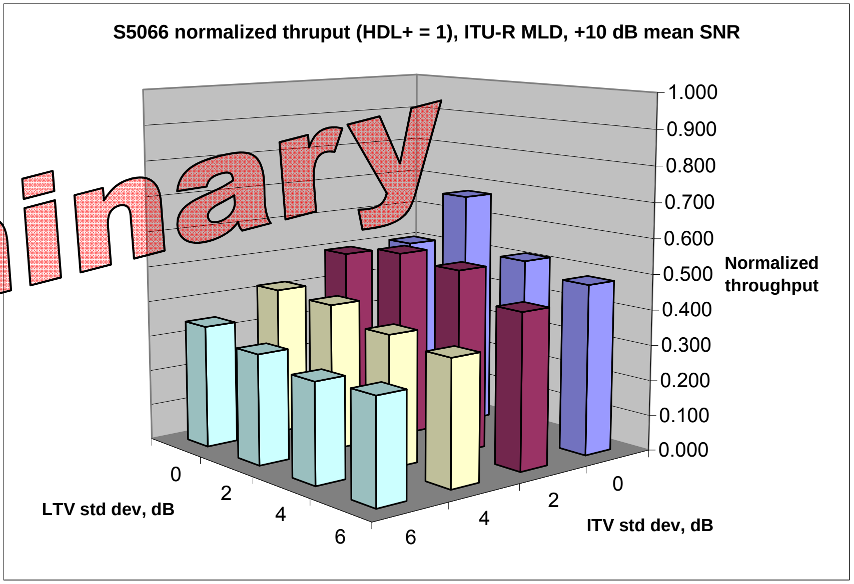
STANAG 5066

LTV

ITV

	0	2	4	6
0	0.503	0.672	0.514	0.481
2	0.498	0.531	0.516	0.438
4	0.419	0.412	0.370	0.351
6	0.345	0.310	0.281	0.292





- Larger difference even without SNR variation, due to multipath and fading per ITU-R ‘Mid-Latitude Disturbed’ profile
- S5066 throughput is less than half that of HDL+ for ITV, LTV std dev = 4 dB

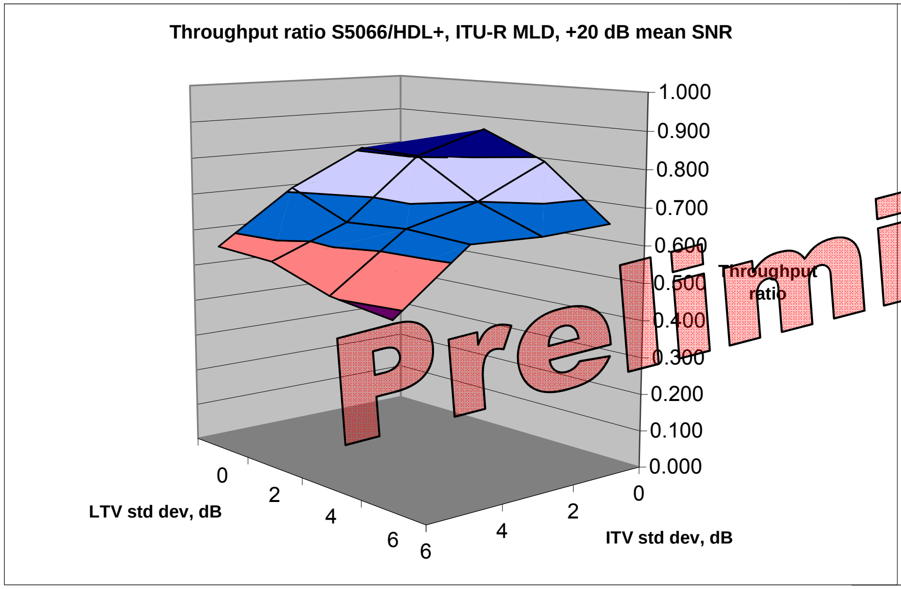
Differential impact of channel variation on STANAG 5066, HDL+

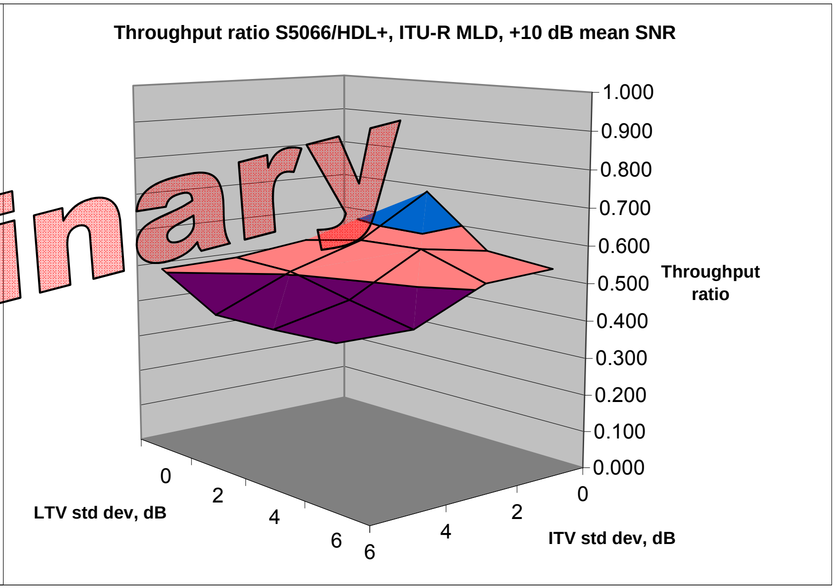
STANAG 5066 / HDL+

ITV \ LTV	0	2	4	6
0	0.763	0.863	0.790	0.644
2	0.807	0.803	0.700	0.634
4	0.710	0.640	0.650	0.640
6	0.568	0.559	0.504	0.481

STANAG 5066 / HDL+

ITV \ LTV	0	2	4	6
0	0.503	0.684	0.541	0.523
2	0.537	0.566	0.572	0.513
4	0.512	0.506	0.463	0.425
6	0.507	0.418	0.419	0.426





- STANAG 5066 throughput falls steadily farther behind that of HDL+ as channel variation increases
- Because of lack of attention to channel variation (and lack of a suitable model), *in-lab performance comparisons have not been an accurate reflection of real-world performance!*

Conclusions and future work

Conclusions:

- Channel quality variation is a significant factor influencing the performance of *adaptive* HF communications techniques
- The traditional ‘Watterson’ HF channel models included in ITU-R Rec. F.1487 do not include this channel quality variation phenomenon, and to this extent may inaccurately characterize HF system performance under real-world conditions
- Harris has developed a model structure representing real-world channel quality variation on ionospheric channels, and techniques for calibrating the model to observed conditions
- The model has been incorporated into a PC-based HF channel simulator (together with the ‘Watterson’ channel model) and used to measure performance of the HF data link protocols STANAG 5066 and STANAG 4538 HDL+
- Our measurements show the incremental redundancy techniques used in HDL+ to be especially beneficial under real-world conditions of channel quality variation
- This channel quality variation model may be worth considering for standardization, possibly in the form of an ITU-R recommendation

Future work:

- Further data collection on other paths: long-haul and NVIS
- Analysis and model-calibration techniques possibly applicable to other data sets (DAMSON?) – calibrate for high-latitude and equatorial conditions