Mark IV Memo #286

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Subject: Write and Write-Crosstalk Tests of ½-Inductance Spin-Physics Prototype and Standard Metrum Heads

Introduction with Main Conclusions

The purpose of the test results reported and analyzed in this memo is to characterize as fully as possible, at 80, 160, and 320 ips write-speed, the write and write-crosstalk performance of an experimental Spin-Physics, 'SP', 35-turn (~ half 'standard' inductance) triple-cap headstack, here designated 'SP35'.

This headstack was also supplied with ~ 12 micrometer (~ 1/2 standard initial minimum) depth-of-gap, intended to increase head efficiency at least 3 dB overall, and to reduce its rolloff in the top 320 ips octave (from 4.5 to 9 MHz).

A substantial improvement in high-speed write-performance, with reduced write-crosstalk due to the ½-inductance design, was expected and indeed observed.

The write-performance of SP35 was compared as directly and unambiguously as possible with that of the two operational standard Metrum headstacks in use at Westford, 'WF'.
One heavily worn stepped headstack was equipped with 'WO', a Mk4 Write-Only head-interface.
The other relatively unworn triple-cap was equipped with 'RW', a Mk4 Read-or-Write interface.
Both interfaces were configured with 1000-ohm write-resistors.
'WFWO' here designates recordings by Westford's worn, stepped Metrum headstack with its WO-interface.
'WFRW' designates test recordings by Westford's standard Metrum triple-cap with its RW-interface.

SP35's write-performance was tested with both RW and WO:

With the RW interface, in tests designated 'SP35RW', SP35's write-performance at 320 ips and 80 ips was found to be comparable to the 160 ips write-performance of several standard-inductance SP headstacks tested earlier (see memo # 285), that is, average parity error rate, 'PER' ~ few x 10^{-4}, was 'marginal', and typically a few channels were out-of-spec but 'processable' with 10^{-2} > PER > 6 x 10^{-4}.
SP35RW performed best at 160 ips write-speed, where 28-channel-average PER = 1.1 x 10^{-4} and worst-channel PER = 3.3 x 10^{-4} were 'marginal' (here defined as 6 x 10^{-4} > PER > 10^{-4}), bordering on 'good' (10^{-4} > PER > 10^{-5}).

With the WO interface, in tests designated ‘SP35WO’, SP35’s write-performance was much better, with average PER ~ 6, 3, and 6 x 10^{-5} and worst-channel PER ~ 1.8 x 10^{-4}, at 320, 160, and 80 ips write-speed. At 320 and 160 ips SP35WO write-performance was ~ on par with that of both standard-inductance Metrum headstacks.

At 80 ips SP35WO’s write performance, though good, was 2 to 3 times worse than that of the Metrum heads, WFWO and WFRW, and than its own best performance at 160 ips write-speed.

Both standard-inductance 48-turn Metrum headstacks with their respective WO and RW interfaces had good to borderline-marginal, though 3 to 5-fold write-crosstalk-degraded, 320 ips mode A write-performance.

The write-performance of new ½-inductance, ½-depth-of-gap, Metrum ‘full’ prototypes on order will be tested when delivered. Little if any write-performance degradation at 320 ips is expected. We have not tested the write-performance of two 35-turn ~ ½-inductance, but ~ 38 um actual depth-of-gap, Metrum ‘partial’ prototypes. With their good read-performance, they were quickly put to operational read-only use on two Haystack Mk4 processor drives.

Overview of Tests

SP35's digital and analog measures of write performance at 80, 160, and 320 ips (digital PER, and analog signal/noise, ‘SNR’, and write-crosstalk spectra) were obtained twice:

- Once, with Westford’s 1000-ohm WO interface, SP35 recorded a data set called SP35WO, and then
- With Westford’s 1000-ohm RW interface, SP35 recorded another data set called SP35RW,

as already indicated. In the following and in the data tables of the appendix, these data sets are also designated 3. and 4. respectively, in order of recording, after 1.WFWO and 2.WFRW.

In both cases 3. and 4., SP35 remained mounted in position #1 near the idler. This position is normally used for Mk4 WO-interfaced headstacks.

Write-crosstalk or –Xtalk, abbreviated ‘WX’, is, broadly defined, any (analog) change in the recording of one channel caused by finite cross-coupling of write-current from the simultaneous write-activity of one or both heads which are physically adjacent in the headstack.

In these tests, with a spectrum analyzer, only power spectra of recordings were observable for quantitative evidence and comparison of WX. Thus, unfortunately, no quantitative phase or time-domain evidence of WX was obtained. And, the power-spectrum measures of WX obtained turned out to be less useful than anticipated.

The 'best' write-voltage for SP35 in SP35WO was initially estimated to be near 12 volts: Error rates of 80 ips mode C recordings at 8, 10, 12, and 16 volts were compared. A deep minimum at 12 volts with only slightly higher error rates at 10 volts was found.

Then, mode A and 'Mixed' mode MA 1000' test recordings were made at 80, 160, and 320 ips [forward only] at both 11 and 13 volt write-voltage, first with the WO and later with the RW interface.

Mode MA is a WX-diagnostic mode (as described in memo #285). In these tests, odd channels recorded coherent monochromatic pure-bandedge 'all ones' signals, while even channels simultaneously recorded independent random-noise.

Signal-to-WX ratio, ‘S/WX’, is the modeA/modeMA spectral power-ratio in dB (here, for odd-numbered channels only).

The spectral points at 6, 8, and 10 9^{th} bandedge (1.5, 2.0, 2.5 MHz, between ‘parity pips’) were logged in order to provide 'unbiased' measures of S/WX. Thereby avoided were potentially misleading and inconsistent biases due to possibly-ambiguously-phased mutually-coherent adjacent-channel interference at the parity pip frequencies (that is, the odd harmonics of 0.25 MHz at 80 ips read-speed).

(Note, the ‘S/WX’ point at the 2.25 MHz bandedge was also logged. It has large negative values and actually represents the ~ 20 dB difference between the big 'all ones' bandedge signal spike in mode MA and the random-signal bandedge parity pip in mode A. The bandedge parity pip is the 9th harmonic of the coherent alternating-sign pulse train component of the odd-parity-formatted random signal.)

For each condition (mode, write-speed, write-voltage, headstack, interface), the 4 spectrum points just discussed as well as a measure of ‘typical’ error-rate were entered into a spreadsheet for analysis and comparison.

Four data sets were obtained from the following test recordings that were made first with the WO- and RW-interfaced standard-inductance Metrum headstacks and then with the ½-inductance SP35 stack, first with WO- then RW-interface ‘transplant’:

1. WFWO, Westford’s operational 1000-ohm Write-Only-interfaced headstack which has the old ‘stepped’ contour design and is heavily worn with remaining shallow depth-of-gap probably comparable to SP35 at ~ 12 um. This ‘reference writer’ recorded modes A and MA at 80, 160, and 320 ips with its pre-optimized ‘operational’ 8 volt write-voltage. These initial test recordings were inadvertently made with 10 % low 9” vacuum. There was prior knowledge of WFWO’s acceptable, though write-crosstalk-degraded 320 ips mode A write-performance. Also of this stepped head’s sensitivity to vacuum (tension) at 320 ips. Consequently, the WFWO data set was augmented, at 320 ips only, with recordings at 12” vacuum, using first 8 volts and then also10 volts write-voltage. The latter reduced average and worst-case PER to 7×10^{-5} and 2×10^{-4} respectively.

2. WFRW, Westford’s operational 1000-ohm Read-or-Write-interfaced headstack which has the newer square-slot standard triple-cap contour design and standard > 25 um depth-of-gap. WFRW had never previously been tested as a writer at any speed. Because of concern about asymmetric capacitive loading by the preamp in the RW interface and reduced efficiency and greater high-frequency rolloff due to the deep gap, there was no a priori expectation of the as-good-as-WFWO 320 ips write-performance that was actually observed. Optimum write-voltage was determined to be 12 volts using 80 ips mode C trials at 10 and 12 volts with max PER = 1.3×10^{-5} at 12 and only slightly higher at 10 volts. Thus WFRW was 3-4 dB less efficient than WFWO due to its deep gap. WFRW was used to record modes A and MA only at 12 volts; if PER at 320 ips had degraded more than with WFWO, a higher high-speed write-voltage would also have been tried to compensate greater rolloff of efficiency. The low ~ 10 MHz resonance of WFRW, loaded by preamp transistor capacitance, may fortuitously have done the same thing.

3. SP35WO, as described above at 11 and 13 volts; 80, 160, and 320 ips; modes A and MA, and finally,

4. SP35RW, similarly.

All 4 sets of test recordings were accumulated on the same Sony D1K tape in order to avoid confusion, especially in PER comparisons, due to sometimes-significant tape-quality differences. Up to 6 passes for 3 write-speeds and 2 write-voltages were used for each set, 1000’ for mode A followed by another 1000’ for mode MA.

Playback conditions were held constant in order to make error-rate and spectrum comparisons between the 4 sets of test recordings (1.WFWO, 2.WFRW, 3.SP35WO, and 4.SP35RW) depend only on differences in write-conditions. Thus all playback was at 80 ips where read-crosstalk, 'RX', is negligible. Also only WFRW, the operational Westford position #2 headstack with its remounted 1000-ohm RW-interface, was used for playback of all 4 sets of test recordings. This headstack is a relatively unworn (depth-of-gap > 25 micrometers) Metrum square-slot triple-cap which probably therefore has ~ 3 dB poorer read-response than a typical <~ 12 um depth-of-gap Metrum headstack.

For each test (set of write-conditions) and for each of the central 28 (# 4 through # 31) channels tested, two independent samples of million-byte raw 'pec' (Parity Error Count) were logged. The lesser of two 'valid' counts was taken as typical or 'edited' pec. Error counts with one or more associated resyncs (bit-slips) were taken to be invalid (see Appendix, discussion of Table 1).

In addition, a spectrum was printed out for each channel for every test. The four discrete marker power levels at 1.5, 2.0, 2.25, and 2.5 MHz (6, 8, 9, and10/9th bandedge frequency) in the printed marker-table were manually entered into an Excel spreadsheet for formal analog performance parameter, SNR, S/WX, etc., analysis and comparisons.

Below is a summary of detailed conclusions, followed by a glossary of abbreviations used in this memo.

Finally, the lengthy Appendix contains 7 tables of 'digested' data. Each table is accompanied by a comprehensive discussion of analysis and interpretation of significant details.

Summary of Detailed Conclusions

1. Three of the four test sets, 1.WFWO, 2.WFRW, and 3.SP35WO, produced comparably good (fully in-spec with PER << 6 x 10^{-4}) digital performance for all 28 channels tested.

    - WFRW and SP35WO Mode C 80 ips recordings (for write-voltage determinations) both yielded 14-even-channel-average PER ~ 10^{-5}. This value is here taken to represent a typical 'un-degraded' digital write-performance 'baseline' -- as read by WFRW at 80 ips. (Note, WFRW, uses a ~ 30 um deep-gap, hence relatively low-efficiency, headstack. Experience shows that 'good' headstacks with less than about 15 um remaining depth-of-gap typically yield even better PER ~ 10^{-6} baseline performance when used at 80 ips to read recordings that are not significantly degraded by high-speed-write-crosstalk and/or by Non-Linear Transition Shift, 'NLTS', industry jargon for a pernicious type of recorded intersymbol interference. The here-observed ~ 19 dB average 2.2 MHz bandedge-SNR would also be expected to increase by 3 – 6 dB to 22 – 25 dB if these recordings were read with a good < 15 um shallow-gap standard-inductance Metrum headstack.)

    - Mode A at 320 ips write-speed yielded even-channel-average PER = 7.9, 8.2, and 5.1 x 10^{-5} for WFWO, WFRW, and SP35WO respectively – roughly an 8-fold or order-of-magnitude error-rate increase with respect to the 10^{-5} mode C at 80 ips baseline.

    - Mode A at 80 ips write-speed yielded average PER = 1.0, 2.1, and 5.1 x 10^{-5} respectively -- no degradation with respect to mode C for WFWO, a 2-fold increase for WFRW, and a 5-fold increase for SP35WO, about equal to that at 320 ips.

- Mode A at 160 ips write-speed yielded average PER = 1.2, 1.9, and 2.3 x 10^{-5} respectively -- same as 80A for WFWO and WFRW, but a 2-fold increase in PER w/r 80C-baseline for SP35WO.

2. SP35 worked better at 160 than at 80 ips write-speed. In memo #285 I reported that several SP headstacks with standard inductance and depth-of-gap showed the same unexpected effect, whereas standard Metrum headstacks never had.

   - Here PER was 2 –3 times higher than at 160 ips at write-speeds of both 80 and 320 ips.

   - The mechanism for digital performance degradation at low write-speed, even in write-crosstalk-free mode C, remains somewhat unclear. However, excessive recorded non-linear intersymbol interference with typical SP headstacks is strongly indicated (see memo #285).

3. SP35's digital write-performance with the RW-interface was much worse than with the WO-interface.

   - Average PER was about 4, 3, and 5 times higher for RW than WO at 80, 160, and 320 ips respectively.

   - At the 320 ips write-speed SP35RW's average PER was ~ 3 x 10^{-4}, and 3 of 28 tested channels 'failed' with 10^{-3} > PER > 6 x 10^{-4} (exceeded specified maximum PER).

4. The low ½-'standard' inductance of SP35 did significantly improve S/WX at 320 ips, as was qualitatively expected.

   - SP35RW had the highest average S/WX(SP35RW, 320) = 12.3 dB, while

   - SP35WO and WFWO had S/WX ~ 10.5 dB, and

   - WFRW had the lowest average S/WX(WFRW,320) = 6.9 dB.

   - The last was also qualitatively expected since, with the standard-inductance head, the low-Q 1000ohm-RW-head-interface resonance was not far from the 320ips bandedge at 9 MHz.

   - Note, the improved 12.3 dB S/WX of SP35RW at 320 ips, which is virtually identical to that at 160 ips, did NOT prevent a 3-fold increase in PER in going from 160 to 320 ips write-speed.

   - Only a 2-fold increase in PER was observed for SP35WO with the same160 to 320 ips write-speed change, in spite of the concomitant ~ 3 dB decrease of S/WX from 13.6 to 10.5 dB.

- Also, the low 6.9 dB S/WX of WFRW compared to the > 3 dB better ~ 10 dB S/WX of WFWO, did not for WFRW result in a larger than ~ 4-fold increase in PER from 160 to 320 ips that was observed for both WFRW and WFWO, nor in significantly higher error rates at 320 ips write-speed.

- Thus these tests, surprisingly, showed no clear relationship between the unambiguous analog measures of write-crosstalk that were painstakingly obtained and the quite ambiguously and complexly affected 'bottom-line' of digital performance in PER.

- Write-crosstalk, like writing itself, is the result of non-linear processes. My understanding of these processes remains heuristic and leads at best to qualitative predictions.

- Standard Metrum and SP35-like SP heads with current-design 1000-ohm WO and RW interfaces may be good enough for 320 ips Mk4 data acquisition. RW could be improved.

- Half-inductance and ½-depth-of-gap Metrum heads are expected to have better high-speed 160 and 320 ips digital write-performance.

5. The write-tests of this memo used only the 1000-ohm WO and RW interfaces with which the operational Mk4 dual-headstack assembly at WF was configured.

    - This was done largely because WFWO was known from earlier tests to have acceptable, though significantly degraded, 320 ips digital write-performance.

    - Unexpected was that the 320 ips digital write-performance of WFRW, in spite of lower anticipated and 3 dB lower observed S/WX, was comparable to WFWO.

    - Mostly 1500-ohm WO and 2000-ohm RW versions of Mk4 interfaces have been 'fielded' however. Compared to the original 1000-ohm versions, the effects of these variants, intended to improve SP write-performance, on actual high-speed write-performance have not yet been determined. Samples of the 'fielded' interface variants, mated first with the 'known' WF headstacks, should be tested by repeating some of the write-tests in this memo, so as to isolate the effects of changing only the write-resistor.

Glossary of Abbreviations and Special Terms

mode A	A normal VLBI data-acquisition mode, in which the central 28 (here, Mk3A), 32 (Mk4), or 36 (VLBA) channels in a headstack simultaneously write VLBI-formatted independent random-signal bit-streams to tape. At high speeds mode A is WX-prone.
mode C	A normal VLBI data-acquisition mode, in which only the central 14, 16, or 18 even- or odd-numbered (non-adjacent) channels in a headstack simultaneously write VLBI-formatted independent random-signal bit-streams to tape. Mode C is 'WX-free'.
mode MA	WX-diagnostic 'Mixed' mode, in which like in mode A all central 28 (here), 32, or 36 channels write simultaneously. Here, odd-numbered channels wrote (mutually-coherent) *ones* signals, while even-numbered channels wrote (independent) *random* signals. The ratio of a mode A spectrum to that of a two-sidedly randomly-interfered-with mode MA *ones* spectrum here defines a channel's S/WX spectrum. Thus S/WX was measured here only for the odd-numbered channels. If needed, complementary even-*ones*/odd-*random* mode MA data for S/WX characterization of even-numbered channels could, of course, also be obtained.
NLTS	Non-Linear Transition Shift: A measure of, in effect, partial erasure of one transition by a too-closely following one, so that linear superposition of isolated step response is no longer a good approximation. This is one kind of non-linear intersymbol interference, which can't be corrected in playback by a linear equalizer. NLTS is the residual change in position of playback peaks (or zero-crossings, with write-waveform-restore equalization such as used in VLBI recorders) that are not removed by an ideal linear equalizer. NLTS and PER increase rapidly with *overdrive.*
ones	The *ones* test-signal is a bandedge square-wave: NRZI modulation code used in magnetic recording channels writes an NRZL '1' as a write-current, hence write-field and thus magnetization, reversal or transition. The longitudinal odd parity of the VLBI track format makes the parity bit associated with an all-ones byte (FF in hexadecimal) a '1' as well. Thus the formatted *ones* test signal is an almost pure bandedge 2-ones-per-cycle square-wave. (The sync-block is not all 1's, but this 'impurity' is here negligible since the sync-block constitutes only 0.8 % of a VLBI-frame.) The *ones* test signal is useful for measuring WX from adjacent *random* channels, because there are no features and very little 'running-noise' baseline-power in the uncorrupted *ones* spectrum below the strong bandedge spike.

overdrive — *Overdrive* here refers to use of 'too high' write-voltage, hence write–current. As consequences, the magnetic write-field distribution or '-bubble' produced in the tape by the head, becomes too large, and magnetization transitions broaden in a complex manner resulting in increased NLTS. One clear analog indication of *overdrive,* readily observed with a spectrum analyzer, at any frequency or wavelength, is an increase in read-output with a decrease in write-voltage. The clearest digital indication of *overdrive* is sharply reduced minimum PER at a sufficiently reduced write-voltage. Overdrive is wavelength dependent. Experience with Metrum heads indicates that the shortest wavelengths invariably are the first to be *overdriven* as write-voltage is increased. Some SP heads have appeared to *overdrive* tape first at mid-band wavelengths and thus to require significant *underdrive* at bandedge (shortest in-band wavelength) in order to minimize NLTS (here only by inference, not direct measurement) and PER.

pec — parity-error-count, per million-successive-byte sample

PER — Parity Error Rate: PER = pec x 10^{-6}

random — The *random* signals used in these tests are VLBI-formatted one-bit sample-streams of low-pass-filtered electronic thermal noise just like 'real' VLBI data. Each *random* parallel channel in these tests was driven by an independent noise-source in order to guarantee that none were coherent in- or out-of-phase copies of each other. Thus the *random* channels are mutually incoherent, unlike the *ones* channels.

RW — Read-or-Write interface: Circuit that interfaces a headstack both for reading or writing via single-ended preamps and write-resistors. The latter serve as bipolar voltage-to-current-source converters of the single-ended AC-coupled outputs of a VLBA or Mk4 Write (driver) module. Here, RW refers specifically to Westford's interface, which was configured with 1000-ohm write-resistors. The RW circuit is loaded by the base capacitance of the preamp's 1st stage emitter-follower.

RX — Read-Xtalk: Read-crosstalk is proportional to speed and head inductance. See memo #285 for more detail. Here, RX was kept small by reading only at a low speed, 80 ips. This was done in order to avoid confusion of RX with the write and WX problems, which needed to be isolated as much as possible for the purposes of this memo, #286.

SP — Spin Physics Inc.

SP35 — SP 35-turn (½-standard-inductance, ½-standard depth-of-gap) prototype headstack. Characterization of SP35's write-performance was the main objective of the tests and analysis of this memo.

SP35RW — SP35 write-test data-set, using Westford's RW interface.

SP35WO — SP35 write-test data-set, using Westford's WO interface.

SNR	Signal-to-Noise Ratio: 'Noise' in this memo is the electronic-noise spectrum measured through the same path as the 80 ips read-signal, including equalizer, but with tape stopped. Noise – Signal power-spectrum is SNR spectrum in dB.
S/WX	Signal-to-WX ratio
underdrive	*Underdrive* here refers to the use of write-voltage too low to maximize response. *Underdrive*, like *overdrive*, is wavelength-dependent. Usually, lowest PER is obtained when write-voltage is set just high enough to maximize the written response near bandedge. Thus, bandedge or shortest-wavelength SNR is maximized for best digital performance, but lower frequencies or longer wavelengths normally remain *underdriven*. Some SP heads behaved differently and required significant bandedge *underdrive* to minimize PER. PER tends to increase slowly with reduced bandedge SNR or increased bandedge *underdrive*.
WF	Westford: Mk4 operational data acquisition and (for this work) test facility.
WFRW	Write-test data-set of WF's standard Metrum triple-cap headstack with its RW-i'face.
WFWO	Write-test data-set of WF's worn std. Metrum stepped headstack with its WO-i'face.
WO	Write-Only interface: Like RW but without functionality of preamp or capacitive loading of its 1st-stage emitter-follower.
WX	Write-Xtalk: Write-crosstalk, broadly defined, is any (analog) change in the recording of one channel caused by finite cross-coupling of write-current from the simultaneous write-activity of one or both heads which are physically adjacent in the headstack.

APPENDIX

Discussion of Tables: Analysis of Digital and Analog Performance Parameter Measurements

Table 1	WFRW & WFWO Error-Rates in Modes A & WX-diagnostic MA
Table 2	SP35RW & SP35WO Error-Rates in Modes A & WX-diagnostic MA
Table 3	SP35RW, SP35WO, WFRW, WFWO Error-Rates Even Channels Only Modes A & C
Table 4	SP35WO & WFRW (a) Linear 'pec' and (b) Logarithmic 'lp.dB' Error-Rate Representation
Table 5	Logarithmic version of Table 2
Table 6	WFRW & WFWO Analog Performance Measures
Table 7	SP35RW & SP35WO Analog Performance Measures

Table 1: WFRW & WFWO Error Rates in Mode A and Write-Crosstalk Diagnostic Mode MA

2R = WFRW 15-Nov-00, Westford Pos.2 Read/Write: write C80 8,10,12v; A,MA,12v at 80,160,320 ips w/ full-depth Metrum TC,1000ohm RW I'face.

1W = WFWO 15-Nov-00, Westford Pos.1 Write-Only:write A,MA 8v,9" at 80,160,320; A320,12" at 8,10v w/ worn stepped Metrum, 1000ohm WO I'face.

mode A

h.m.s,v,vac	**max.pec**	**pe.count**	**av28\ch#**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	max/typ	max/av	typ/av
2A80,12	75	2R pec	29	24	24	18	59	33	14	24	53	32	33	12	65	28	75	14	28	6	20	16	33	12	14	24	26	29	27	18	49	3.0	2.6	0.86
2A160,12	75	2R pec	28	4	20	18	53	37	27	20	33	22	37	10	22	41	20	8	75	24	29	12	47	12	39	20	43	18	61	14	12	3.2	2.7	0.84
2A320,12	274	2R pec	102	4	100	63	157	95	106	126	93	63	162	71	274	95	79	150	158	59	89	97	154	43	83	112	146	75	61	91	59	3.1	2.7	0.85

mode A

h.m.s,v,vac	**max.pec**	**pe.count**	**av28\ch#**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	max/typ	max/av	typ/av
1A80,8v,9"	55	1W pec	18	4	12	10	26	18	12	10	55	28	43	10	39	10	28	4	28	6	16	2	24	10	8	18	37	0	33	8	12	4.2	3.0	0.72
1A160,8v,9"	69	1W pec	16	6	14	12	26	8	8	10	26	14	29	14	69	16	10	10	8	24	10	8	20	14		6	14	28	18	2	12	5.2	4.3	0.82
1A320,8v,9"	502	1W pec	168	14	140	130	128	140	205	83	175	167	437	256	502	378	39	37	258	163	149	104	151	134	169	217	108	102	219	47	56	3.8	3.0	0.78
1A320,8v,12"	384	1W pec	131	18	157	128	37	203	126	63	57	265	238	167	91	384	43	140	124	342	112	86	37	240	100	136	35	217	81	28	14	4.0	2.9	0.74
1A320,10v,12"	211	1W pec	72	16	75	30	33	110	134	22	81	138	130	67	112	211	16	53	116	177	43	31	59	97	28	45	41	99	18	16	8	4.0	2.9	0.74

WX-diagnostic mode MA, **e**ven **r**andom **m**ixed mode channels

even.ran.mA	**max.pec**	**pe.count**	**av14even**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**	max/typ	max/av	typ/av
2erm80,12	26	2R pec	10	6	4	4	26	6	4	8	24	4	8	10	8	8	14	3.3	2.7	0.83
2erm160,12	83	2R pec	10	0	2	4	2	0	0	10	83	8	4	6	10	4	8	20.6	8.2	0.40
2erm320,12	12	2R pec	5	2	2	6	12	4	8	12		4	4	2	6	4	2	2.7	2.3	0.85

WX-diagnostic mode MA, **e**ven **r**andom **m**ixed mode channels

even.ran.mA	**max.pec**	**pe.count**	**av14even**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**	max/typ	max/av	typ/av
1erm80,8v,9"	14	1W pec	6	2	4	12	2	14	8	12	6	4	4	0	4	12	6	2.8	2.2	0.78
1erm160,8v,9"	10	1W pec	6	0	8	4	6	8	6	10	6	8	0	4	8	4	10	2.1	1.7	0.79
1erm320,8v,9"	83	1W pec	35	4	24	33	14	51	83	81		65	10	26	28	26	10	3.2	2.4	0.74

WX-diagnostic **o**dd **1**'s **m**ixed mode channels

odd.ones.mA	**max.pec**	**pe.count**	**av14odd**	**5**	**7**	**9**	**11**	**13**	**15**	**17**	**19**	**21**	**23**	**25**	**27**	**29**	**31**	max/typ	max/av	typ/av
2o1m80,12	10	2R pec	1	0	2	0	2	0	0	0	0	0	0	0	10	0	2	19.9	8.8	0.44
2o1m160,12	2	2R pec	0	0	2	0	0	0	0	0	2	0	0	0	2	0	0	7.5	4.7	0.62
2o1m320,12	8	2R pec	1	0	0	0	0	2	2	8	0	0	4	0	2	0	2	10.0	5.6	0.56

WX-diagnostic **o**dd **1**'s **m**ixed mode channels

odd.ones.mA	**max.pec**	**pe.count**	**av14odd**	**5**	**7**	**9**	**11**	**13**	**15**	**17**	**19**	**21**	**23**	**25**	**27**	**29**	**31**	max/typ	max/av	typ/av
1o1m80,8v,9"	2	1W pec	0	0	0	0	2	0	2	0	0	0	2	0	0	0	0	7.5	4.7	0.62
1o1m160,8v,9"	30	1W pec	3	0	0	0	30	0	4	8	2	0	2	0	0	0	0	31.2	9.1	0.29
1o1m320,8v,9"	43	1W pec	13	8	10	43	0	41	20	35	0	2	2	4	2	10	2	7.2	3.4	0.47

Notes:

pec — Edited **p**arity **e**rror **c**ount is lesser of two valid million byte parity error count samples. Sample is invalid if there are one or more associated resyncs. If both are invalid, pec is invalid and channel is not included in average.

(dark red)	invalid pec	
(red)	600 < pec	channel fails VLBA spec
(yellow)	300 <= pec <= 600	high marginal
(light yellow)	100 <= pec < 300	low marginal
(green)	10 <= pec < 100	good
(light cyan)	1 <= pec <= 9	excellent
(blue)	pec = 0	typical PER < 10^-6

Table 1 WFRW & WFWO Error-Rates in Modes A & WX-diagnostic MA

Defined in the key at the bottom of Table 1 is a linear measure of 'typical' digital channel performance (parity-error-rate x 10^6) I call edited Parity-Error-Count or '**pec**'. Edited **pec** is tabulated for each channel, with one row for each combination of write-conditions used (write-speed, write-voltage, vacuum, head/interface, mode).

For each condition and channel, two independent samples of raw parity-error-count per million-bytes were logged. The edit criteria applied attempted expeditiously to remove the bias of atypically large and false error counts. These are usually due to major tape flaws (dropouts), some of which cause bit-slip.

Bit-slip is followed by a 50 % 'false' error-rate that persists until 'resync' at the next frame-boundary is possible. By design, detection of an error-free VLBI sync-word in any unexpected position is needed to 'resync' the longitudinal VLBI format. Resync restores the byte-boundary timing needed to correctly check parity. On average, a single random bit-slip will yield ¼-frame or 625 'false' parity-error counts in addition to the true errors produced by the flaw prior to bit-slip.

Thus a raw error-count sample was considered invalid if there were any associated resyncs, as logged by a field-system parity-check procedure.

In order to free the edited count of bias due to bit-slip-free dropouts, the smaller of two valid raw error-counts was taken to be representative. If only one was valid, it was taken to be representative by default. If both raw counts were invalid, the edited pec measurement was considered invalid.

Color-coding of the background of each pec entry, as defined in the key, facilitates diagnostic data inspection and comparison. In each row, the entry for the channel with maximum pec is 'boxed' for similar reasons.

Table 1 shows that in mode A at 80 and 160 ips write-speed both WFRW and WFWO exhibited good (pec < 100) to excellent (pec < 10) performance. The background color-coding results in fields of green with some blue.

At both 80 and 160 ips write-speed average pec was about 30 and 20 for WFRW and WFWO respectively. This was about 3 times the 'baseline' pec ~ 10 and 6 respectively observed in write-crosstalk-free mode MA at these speeds (or in 80 ips mode C for WFRW).

Max.pec, pec of the worst channel, was 3 to 4 times the 28-channel average in all cases. Note that max.pec corresponded to a different channel for each speed and head/interface. Thus, there were no obvious 'bad-actor' or 'outlier' write- or read- channels.

At 320 ips write-speed, best average pec ~ 100 and 70 for WFRW and WFWO respectively. This was about 10 times the 'baseline' pec observed in crosstalk-free mode MA at 80 and 160 ips. It was also ~ 3.5 times worse than 80/160 ips mode A performance.

Nevertheless even at 320 ips most channels were good (green) while the rest, 11 and 8 channels for WFRW and WFWO respectively, all had 'low marginal' (light yellow, pec < 300) performance, with max.pec ~ 270 and 210 respectively.

Note, though WFRW and WFWO exhibited quite comparable digital performance, WFWO was consistently somewhat better than WFRW: In every test, error ratio was pec(WFWO)/pec(WFRW) ~ 2/3.

For WFWO at 320 ips in mode A, best write-performance was ultimately obtained by

1. raising vacuum from 9" (unintentionally 10 % low) to 12" (intentionally 20 % high, in accord with earlier test experience with this stepped head at 320 ips), and

2. increasing write-voltage from 8 volts (predetermined optimum operational value for writing at 80 and 160 ips) to 10 volts. (10 volts was known from earlier tests to greatly degrade 80 ips, but to improve 320 ips, write-performance.)

Average 320 ips pec went from

- 168 at 8v, 9” to
- 131 at 8v, 12” to
- 72 at 10v, 12”, a substantial improvement,

while average bandedge SNR went from 16.9 to 17.2 to 18.3 dB (see Table 6). The latter is a correlated, significant improvement in an important analog figure-of-merit. Only the last best 320 ips SNR at 10v, 12” was on par with the 18.0 dB 80 ips and 18.5 dB 160 ips values at 8v, 9”.

The 2 dB boost in optimum 320 ips write voltage for WFWO was not a surprise: A 1- 2 dB rolloff of head-efficiency to the 9 MHz 320 ips bandedge is expected even for the worn stepped Metrum head. A small 320 ips spacing increase could also have produced a wavelength-independent depth-of-recording loss that may have been compensated with increased write-voltage (as long as the head didn’t saturate).

WFRW on the other hand did not need a similar external write-voltage boost for its optimum 320 ips write-performance. This is in spite of the essentially unworn triple-cap’s ~ 30 um deep gap, which typically causes ~ 5 dB efficiency rolloff to 9 MHz in new standard Metrum heads. Approximately the correct frequency-dependent boost may have been provided by the low-Q resonance of the 1000-ohm RW-interface near the 320 ips bandedge.

(The WO-interface, without the ~ 8 pF load of the EF transistor, resonates at much higher frequency and so doesn’t much boost the 320 ips bandedge write-current.)

Evidence that the efficiency-rolloff of the deep-gap standard-inductance head was compensated by the extra capacitance of the RW interface is that the average bandedge SNR is virtually independent of write-speed: Measured values were 18.7, 19.1, and 19.1 dB for writing at 80, 160, and 320 ips respectively, as shown in Table 6.

The error statistics of write-crosstalk-diagnostic ‘mixed’ mode MA are also shown in Table 1, separately for the even-numbered independent random-data channels and the simultaneously written odd-numbered coherent ‘ones’ channels.

These mode MA error statistics are not directly relevant for the primary purpose of mode MA recordings, which is to provide spectra for unambiguous S/WX (signal/write-crosstalk) measurements.

A clear relationship between S/WX and error-rate was anticipated. But, contrary to expectation as further discussed in connection with Tables 6 and 7, no obvious relationship was found.

However, a few characteristics of mode MA error statistics should be noted:

1. The independent-random-noise (here even-numbered) channels in mode MA had about 3.5 times lower error-rate than in mode A, and about the same ‘baseline’ error-rate as in write-crosstalk-free mode C (see Table 3). The apparent write-crosstalk-free behavior of most MA random channels was expected, as a result of mutual cancellation of anti-phased coherent ones interferences from the two adjacent simultaneously-writing channels. The anti-phasing of alternate odd or even channels is due to the layout of the head-interface board (assuming in-phase inputs).

2. Random-channel # 4 had Ones-channel # 5 as its only active interfering neighbor, since only the central 28 channels, # 4 through # 31, were used in these tests. Though error-rate was not

significantly affected, inspection of # 4's spectrum showed the one-sided 'ones' (monochromatic bandedge) interference from #5 as a few dB increase in the size of the bandedge 'parity pip'.

3. Random-channel # 18 typically had high error rates and high probability of bit-slip especially at the highest 320 ips write-speed. Its spectrum showed high bandedge interference with an 8 –10 dB 'oversize' bandedge pip. The interference was also evident in modulation and synchronization instability of the eye pattern. The cause of this behavior was in-phase (instead of canceling) coherent ones interference from the two adjacent channels # 17 and 19. This constructive interference was found to be due to the Mk4 formatter output design not taking into account the mid-connector inversion of complementary lines in VLBA/Mk4 recorder-internal parallel data cables. Thus, odd # 19 – 35 were driven to the head-interface board in opposite phase with respect to odd # 1 – 17. The alternating-phase output-w/r-input layout of the odd interface board, produced a second relative phase reversal of # 17 with respect to # 19, thereby making that pair alone in-phase.

4. 'Ones', unlike 'random', recordings are by nature free of inter-symbol interference. Thus, the very lowest error-rates of order $< 10^{-6}$ are expected for 'ones'. In MA the observed 'ones' error rates rarely rose above 10^{-5}, in spite of substantial write-crosstalk from the adjacent random channels. The spectra of 'ones' recordings in MA were needed for isolating and quantifying write-crosstalk. The low associated MA-ones and MA-random error-rates should not be taken to be representative of good system performance. Separate mode A data was needed for realistic measures of digital performance.

Table 2: SP35RW and SP35WO Error Rates in Mode A and Write-Crosstalk Diagnostic Mode MA

SR = SP35RW Spin Physics 35-turn half-L shallow-gap TC w/ 1000ohm Read-or-Write I'face in Pos.1: 3-speed, 2-voltage write 29-Nov-00 WFRW 80ips read 22-Dec-00

h.m.s,v,vac	max.pec	pe.count	av28\ch#	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
A80,11	670	SR.pec	262	47	169	53	473	163	335	254	418	209	272	119	510	340	670	168	265	256	219	91	644	109	445	98	177	166	510	81	79
A80,13		SR.pec																													
A160,11	605	SR.pec	226	116	164	97	501	221	449	122	605	217	480	79	464	499	234	195	187	207	305	161		85	160	77	134	87	189	33	24
A160,13	331	SR.pec	**108**	18	65	37	163	110	116	96	132	225	81	114	154	104	155	92	102	146	75	35	298	37	63	331	65	81	71	32	22
A320,11	1838	SR.pec	443	219	204	154	664	611	936	99	772	280	926	116	674	790	562	668	305	305	639	406	1838	173	128	171	384	130	195	28	26
A320,13	926	SR.pec	**306**	65	112	73	394	254	300	191	467	222	425		642	392	406	244	374	384	278	154	696	166	274	225	129	319	926	57	97
contras:	2500		**385**	65	112	73	394	254	300	191	467	222	425	2500	642	392	406	244	374	384	278	154	696	166	274	225	129	319	926	57	97
A160,13-11v con.del.pec	3 of 28		99									8		35												254					
A320,13-11v con.del.pec	10 of 28		162							92									69	79					146	54		189	731	29	71
if count resync as pec = 2500 :			384							92				2384					69	79					146	54		189	731	29	71

even.ran.mA	max.pec	pe.count	av14even	4	6	8	10	12	14	16	18	20	22	24	26	28	30
erm80,11	265	SR.pec	122	63	33	144	167	175	95	256	265	138	120	63	43	116	33
erm80,13		SR.pec															
erm160,11	412	SR.pec	144	93	120	240	87	219	73	412	307	134	201	45	31	24	30
erm160,13	318	SR.pec	**106**	16	26	79	104	93	154	147		65	24	33	318	215	104
erm320,11	1163	SR.pec	331	138	351	775	155	420	203	1163		395	368	134	95	81	24
erm320,13	236	SR.pec	**96**	45	20	211	35	140	116	236	136	65	96	71	81	75	18

odd.ones.mA	max.pec	pe.count	av14odd	5	7	9	11	13	15	17	19	21	23	25	27	29	31
o1m80,11	35	SR.pec	7	0	0	2	10	14	4	6	6	4	35	6	8	0	0
o1m80,13		SR.pec															
o1m160,11	49	SR.pec	6	0	49	0	4	0	4	0	4	8		0	5	0	0
o1m160,13	4	SR.pec	**1**	0	0	2	2	0	2		0	0	4	0	2	0	0
o1m320,11	98	SR.pec	11	0	0	0	0	8	0		4	98		8	12	0	0
o1m320,13	28	SR.pec	**4**	4	28	4	4	0	2	0	4	0	2	0	6	0	0

SW = SP35WO: SP35turn w 1000ohm Write-Only i'face write C80 8,10,12,16v, then A,MA 80,160,320ips (11v.22-Nov-00,13v.28-Nov-00)

pe.count: min of 2 parity-error-per-million-bytes counts, blank if both have resyncs

h.m.s,v,vac	max.pec	pe.count	av28\ch#	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
A80,11	193	SW pec	**62**	26	61	28	53	73	193	29	20	83	79	26	49	75	71	22	83	112	28	33	22	37	73	57	140	73	59	43	94
A80,13	761	SW pec	68	16	24	8	29	24	55	8	14	89	100	22	28	77	761	95	65	33	16	14	24	6	22	33	155	45	71	49	24
A160,11	172	SW pec	**34**	35	26	10	20	37	73	10	14	63	172	18	33	35	83	16	16	32	24	10	91	6	20	22	16	16	47	12	4
A160,13	220	SW pec	50	10	26	24	30	33	91	35	12	116	71	43	28	71	220	79	55	26	41	18	24	8	37	26	37	26	158	43	22
A320,11	465	SW pec	133	26	140	6	45	200	464	12	79	225	254	57	108	465	315	31	57	150	99	28	217	73	69	39	59	364	96	33	10
A320,13	181	SW pec	**64**	10	81	4	43	146	181	6	41	144	67	39	104	85	79	28	130	110	77	14	118	20	33	24	102	81	20	0	16
A80,11-13v con.del.pec	19 of 28		35	10	37	20	24	49	138	21	6			4	21				18	79	12	19		31	51	24		28			70
A160,11-13v con.del.pec	6 of 28		34	25							2		101		5					6			67								
A320,13-11v con.del.pec	3 of 28		41																73								43				6

even.ran.mA	max.pec	pe.count	av14even	4	6	8	10	12	14	16	18	20	22	24	26	28	30
erm80,11	335	SW pec	38	2	10	20	0	67	2	49	335	2	8	2	6	20	4
erm80,13	112	SW pec	**18**	8	2	18	2	112	4	45		6	6	0	10	8	8
erm160,11	26	SW pec	8	2	2	6	2	26	12	22	10	2	8	2	10	2	0
erm160,13	12	SW pec	**6**	4	6	12	6	12	12	6		12	0	0	4	4	4
erm320,11	3699	SW pec	717	81	10	1109	22	883	148	1086	28	1340	14	1567	24	3699	20
erm320,13	47	SW pec	**14**	28	2	30	8	4	47	22		12	16	2	6	8	0

odd.ones.mA	max.pec	pe.count	av14odd	5	7	9	11	13	15	17	19	21	23	25	27	29	31
o1m80,11	2	SW pec	0	0	0	0	2	0	0	2	0	2	0	0	0	0	0
o1m80,13	6	SW pec	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0
o1m160,11	6	SW pec	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0
o1m160,13	2	SW pec	0	0	0	0	0	0	0	0	2	0	2	0	2	0	0
o1m320,11	18	SW pec	4	0	2	2	2	12	18	2	0	0	4	4	6	2	0
o1m320,13	6	SW pec	**1**	0	0	2	0	0	0	0	0	0	6	0	0	0	0

Table 2 SP35RW & SP35WO Error-Rates in Modes A & WX-diagnostic MA

This table is similar to Table 1 but for test recordings made with the ½-inductance ½-depth-of-gap experimental SP headstack, SP35.

The test-recordings called SP35WO used the WO-interface transferred from Westford's WFWO subassembly.

The recordings called SP35RW used the same headstack, SP35, but the RW-interface from Westford's WFRW subassembly.

SP35 remained in position #1 of a dual-stack mount, which is closest to the capstan, and in which SP35 had earlier undergone the read-tests that are described in memo #285. Care was taken not to accidentally shift SP35 or either of Westford's Metrum headstacks in their mounts in the several interface 'transplant' operations required for these test recordings and to restore Westford's operational assembly thereafter.

Subsequent reading of all test recordings both for error-rate and spectrum samples was done with the restored WFRW.

Mode C 80 ips test recordings with SP35WO at 8, 10, 12, 16 volts determined that optimum write voltage which produced the lowest worst-case error-rate was near 12 volts as shown in Table 3. It was decided to bracket this voltage by recording all SP35 mode A and MA write-tests at both 11 and 13 volts. Thus dependence of digital and analog performance parameters on write-voltage was probed. In particular, I wanted to see if there was a significant increase in optimum write-voltage with write-speed to 320 ips (as was the case, discussed above, for WFWO).

SP35WO performed well at all write-speeds, certainly as well or very slightly better than WFWO and WFRW at 320 ips. SP35WO's best performance at 160 ips 11 v, av.pec = 34, was also comparable to WFRW's av.pec = 28 at 160 ips 12 v. Both at 80 ips 11 v with av.pec = 62, and at 320 ips 13 v with av.pec = 64, SP35WO's error rates increased by a factor of 2.

SP35RW, SP35 with the RW-interface instead of the WO- interface, performed much more poorly:

At 80 ips 11 v with av.pec = 262 and at 320 ips 13 v with av.pec = 306, SP35RW's error-rates were more than 4 times higher than SP35WO's.

For SP35RW at 80 and 320 ips, 2 and 3 channels respectively were also somewhat over the formal max.pec spec with 600 < pec < 1000, while all SP35WO channels had pec < 200 at all 3 write-speeds.

Like SP35WO, SP35RW had best performance at 160 ips 13 v, where av.pec = 108 was about 3 times av.pec = 34 of SP35WO at 160 ips 11 v.

The poorer performance of SP35RW is in spite of SP35's low inductance, which pushes the SP35RW resonance far beyond the 9 MHz 320 ips bandedge. Thus, significantly resonance-enhanced write-crosstalk was not expected, and, indeed, was not observed (see Table 7). In fact, at 320 ips 13v, bandedge S/WX = 12.3 and 10.5 dB for SP35RW and SP35WO respectively, was almost 2 dB better for SP35RW than SP35WO – for unknown reasons.

At lower write-speeds S/WX was identical for SP35RW and SP35WO.

Bandedge SNR was also independent of speed to within ½ dB and the same for SP35RW and SP35WO.

Thus there is no obvious hint in the analog measurements as to the cause of the degraded digital write-performance of SP35 with the RW-interface compared to that with the WO-interface.

As puzzling and in need of explanation is the already mentioned unexpectedly good digital performance at 320 ips of WFRW in spite of very low average bandedge S/WX = 6.9 dB due to close head/interface resonance.

'Contra' analysis: Contras were here defined as channels whose pec dependence on write-voltage was opposite that of the average of all channels in a test ensemble.

A striking example was in the comparison 11 vs. 13 volt writing at 80 ips with SP35WO, for which av.pec/max.pec were 62/193 and 68/761 respectively. In this case, more than half, 19 of 28, tested channels were contras -- made conspicuous in Table 2 by using red pec numbers. While most channels performed somewhat better at 13 than 11 volts (13 v average pec = 42 if channel # 17 with max.pec = 761 is excluded), # 17's performance was super-sensitive in the opposite direction: The < 20 % increase in write-voltage from 11 to 13 volts increased # 17's pec from 71 to 761, a 10-fold increase from ~ average performance at 11 v.

Inspection of bandedge SNR dependence on write-voltage in Table 7 shows that #17 also had 2.2 dB higher SNR at 13 than 11 volts, while the average SNR increase with write-voltage was only 0.6 dB. Thus #17 of SP35 behaved like many standard SP heads (see memo #285) in that it alone required > 2 dB bandedge underdrive to achieve an acceptable minimum error-rate.

#17 is an outlier that appears to suffer from severe intersymbol interference at substantially lower write-voltage than the other channels in SP35. Convincing evidence can be found in Table 7 (to be further discussed) and in a direct comparison of the 11 and 13 v A80 spectra of #17: The 11v spectrum is 'normal', peaked at ~ $5/9^{th}$ bandedge with about 5 dB rolloff to bandedge. The 13 v spectrum on the other hand is quite abnormal, peaked at ~ $7/9^{th}$ bandedge with only ~ 2 dB rolloff to bandedge. While bandedge output increased more than 2 dB, output at $5/9^{th}$ bandedge actually decreased about 1 dB with the write-voltage increase from 11 to 13 v. This clearly indicates that # 17's mid-band and longer wavelengths are substantially overdriven at 13 volts, consistent with the order-of-magnitude increase in error-rate observed at the higher write-voltage.

MA notes:

For SP35WO at 320 ips 11 v, alternate even random channels, except #4, had anomalously high pec's from about 1000 to 4000. A possible explanation is a here 'once-observed' formatter initialization anomaly (of NRZL->NRZI converting toggling flip-flops) such that certain adjacent odd ones channels were output anti-phase instead of in-phase. This would produce strong in-phase instead of canceling anti-phase interference, hence high error counts, because (as has already been mentioned) the head-interface board layout happens to be such as to alternate the polarity for successive even or odd channels.

Both the random and ones MA spectra for the 11v run at 320 ips were atypical in a way consistent with this picture: The random-data spectra had their normal ~ 3 dB bandedge parity pip essentially wiped out. Except # 4, which had only one interfering 'ones' neighbor in # 5; # 4's bandedge pip was enlarged to ~ 8 dB. The odd-channel 'ones' spectra, which normally show no parity pip interference from adjacent random channels, alternated a 5 dB pip at $7/9^{th}$ bandedge for channels # 5+4n, with 10 dB at $7/9^{th}$ and 5 dB at $5/9^{th}$ bandedge for channels # 7+4n.

Note that the parity pips, Fourier components (odd harmonics) of the alternating-sign pulse train that is added to independent random bit-streams by the odd-parity NRZI format, constitute a coherent signal component with deterministic phase relationships just like those of the coherent ones channels. The parity pips from two adjacent random interfering channels are normally missing from an interfered-with ones channel for this reason; the coherently phased pulse-train parts of the two adjacent formatted independent random bit streams are normally out-of phase so that their interference cancels.

Thus, because the 0 vs.180 degree relative phasing of the coherent signal components in the pair of neighboring channels is not specified and is subject to vagaries of layout of boards and connectors as well as initialization of the NRZI modulation code, only the randomly-phased portions of the formatted random data spectra between the parity pips were 'trusted' to provide unbiased analog measures of crosstalk:

Therefore, the primary measures of SNR and S/WX in Tables 6 and 7 were evaluated at 2.2 MHz by quadratic interpolation of 3 directly logged spectral marker points at 1.5, 2.0, and 2.5 MHz, halfway between parity harmonics 5&7, 7&9, and 9&11 respectively.

Note the high probability of sync-loss, evident as invalid pec measurements indicated by maroon blank entries, in random channel #18 both for SP35WO and SP35RW, and in ones channel #17 for SP35RW.

Both #17 and #18 mid-stack channels were inadvertently configured (as was pointed out earlier) such that coherent interference from # 16 & 18 for the former and # 17 & 19 for the latter was in-phase, and therefore resulted in worst-case interference (whereas all other channels with two-sided coherent interference, had the two neighbors 180 degrees out-of-phase, which resulted in the best-case, cancellation of coherent interference).

A remarkably large threshold-crossing-like increase of ones-to-random write-crosstalk was observed in conjunction with the small increase of test write-voltage from 11 to 13 volts:

For SP35WO random channel #18 at 160 ips at 11 v for example, pec = 10 indicated very good performance. Inspection of the corresponding spectrum showed a 'normal' 3 dB bandedge pip; thus, there was no obvious sign of write-crosstalk from the adjacent in-phase ones channels # 17 & 19.

By contrast at 13 v, that is, only 2 dB higher write-voltage, there were already large numbers of resyncs (bit-slips) so that valid pec measurements could not be obtained. The 13 v spectrum showed a 10 dB 'enhancement' of the bandedge parity pip. Or, equivalently, a bandedge signal only 12 dB smaller than that of its 'ones' neighbors. Thus the 25 % amplitude written-in bandedge interference was enough to make the random channel unusable. S/WX (ones #17&19 to random #18 at 160 ips) went from > 22 dB at 11 volts to ~ 12 dB at 13 volts.

The S/WX measurements in Tables 6 and 7 are for random-to-ones write-crosstalk, not for the ones-to-random crosstalk just discussed. Random-to-ones crosstalk had a much milder dependence on write-voltage:

For SP35WO at 160 ips for example, average S/WX (random-to-ones, 1.5, 2.0, 2.5 MHz values interpolated to 2.2 MHz) dropped only ~ 2 dB from 13.6 dB at 11 volts to 11.5 dB at 13 volts. Random-to-ones S/WX for the worst channel, # 17, dropped 3 dB, from 12 dB at 11 v to 9 dB at 13 v. Though pec also increased from 83 to 220 in this case for this channel as might be expected with a reduction of S/WX, counterexamples are numerous: For example, the very lowest S/WX = 4.8 dB was observed for channel #17 of WFWO at 320 ips, 8 v, 9" vacuum (in Table 6); yet (in Table 1) pec = 39 was good, 3rd best of 28!

Table 3: SP35RW, SP35WO, WFRW, WFWO Error Rates, Even Channels Only, Mode A and Mode C

4. SP35RW																	
h.m.s,v,vac	**max.pec**	**pe.count**	**av14even**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**
A80,11	340	SR.pec	154	47	53	163	254	209	119	340	168	256	91	109	98	166	81
A160,13	331	SR.pec	**104**	18	37	110	96	225	114	104	92	146	35	37	331	81	32
A320,13	392	SR.pec	**211**	65	73	254	191	222		392	244	384	154	166	225	319	57

3. SP35WO																	
h.m.s,v,vac	**max.pec**	**pe.count**	**av14even**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**
C80,12	26	SW pec	**9**	10	4	8	4	26	8	26	2	20	0	6	10	0	6
A80,11	112	SW pec	**51**	26	28	73	29	83	26	75	22	112	33	37	57	73	43
A80,13	95	SW pec	37	16	8	24	8	89	22	77	95	33	14	6	33	45	49
A160,11	63	SW pec	**23**	35	10	37	10	63	18	35	16	32	10	6	22	16	12
A320,13	146	SW pec	**51**	10	4	146	6	144	39	85	28	110	14	20	24	81	0

2. WFRW																	
h.m.s,v,vac	**max.pec**	**pe.count**	**av14even**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**
2C80,8v	85	2R pec	43	32	14	41		85	47	74	45	37	67	39	53	12	8
2C80,10v	81	2R pec	18	18	2	6	14	57	4	81	16	6	10	14	4	6	10
2C80,12v	36	2R pec	9	4	4	12	6	36	4	14	10	8	6	4	12	2	8
2A80,12	33	2R pec	21	24	18	33	24	32	12	28	14	6	16	12	24	29	18
2A160,12	41	2R pec	19	4	18	37	20	22	10	41	8	24	12	12	20	18	14
2A320,12	150	2R pec	82	4	63	95	126	63	71	95	150	59	97	43	112	75	91

1. WFWO																	
h.m.s,v,vac	**max.pec**	**pe.count**	**av14even**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**
1A80,8v,9"	28	1W pec	10	4	10	18	10	28	10	10	4	6	2	10	18	0	8
1A160,8v,9"	28	1W pec	12	6	12	8	10	14	14	16	10	24	8	14	6	28	2
1A320,10v,12"	211	1W pec	79	16	30	110	22	138	67	211	53	177	31	97	45	99	16

Table 3 SP35RW, SP35WO, WFRW, WFWO Error-Rates Even Channels Only Modes A & C

Table 3 facilitates comparison of the four head/interface combinations tested. It also facilitates comparison of mode A and the 80 ips mode C write-voltage-determination tests of WFRW and SP35WO. Since mode C here used only the even channels, in order to avoid bias in comparing mode A and mode C, only even channel data is shown in this table for mode A as well as mode C. At each write-speed only the best av.pec conditions (that is, write-voltage and vacuum, if multiple conditions were tested) are tabulated, with one exception: For SP35WO at 80 ips pec's are tabulated for write-voltages of both 11 and 13 v, because the even-14 average pec were lower at 13 volts while the 28-channel av.pec were lower at 11 (due to 'outlier' #17 already discussed).

Note:

- Only WFRW and SP35WO were tested in mode C and only at 80 ips write-speed. Both yielded av14even.pec = 9 (both at a best write-voltage of 12 v). Thus, 'un-degraded' baseline performance was judged to be PER ~ 10^{-5}.
- In mode A WFWO write performance at 80 and 160 ips with av.pec = 10 and 12 respectively was about the same as 'baseline', 80 ips mode C for WFRW and SP35WO, that is, 'un-degraded'.
- In mode A WFRW at 80 and 160 ips and SP35WO only at 160 ips were worse than 'baseline' by a factor of ~ 2 with PER ~ 2×10^{-5}.
- In mode A SP35WO at write-speeds of both 80 and 320 ips was worse by a factor of ~ 5 with PER ~ 5×10^{-5}. At 320 ips this is the best (least degraded) write performance observed, comparable to PER ~ 8×10^{-5} for the two standard-inductance Metrum stacks in WFWO and WFRW.
- SP35RW, with the same headstack as in SP35WO and the same RW-interface as in WFRW, was much worse than baseline PER ~ 10^{-5}, by factors of ~ 15, 10, and 20 at write-speeds of 80, 160, and 320 ips respectively. Only at the 'best' write-speed, 160 ips, did all 28 tested channels meet the PER < 6×10^{-4} specification. At 80 and 320 ips, only 6 and 4 of 28 channels respectively had good performance with pec < 100.
- SP35RW had about 4 times worse digital performance than SP35WO at all write-speeds. This appeared to be due exclusively to replacing the WO- with the RW-interface. The much poorer performance of SP35 with the RW-interface lacks a fully convincing explanation, especially in light of the good performance observed with WFRW. Nevertheless, a comparison of analog performance parameters discussed in conjunction with Table 7 suggests that capacitive loading of the write circuit by the RW preamp's 1st-stage emitter-follower was the main cause of poor write-performance with the ½-inductance ~ 10 uH SP headstack. It was concluded that the RW-interface can probably be improved to write as well as WO driving ½- as well as standard-inductance heads: Substitution of a low-capacitance < 2 pF transistor for the current 3906 1st-stage emitter-follower may well be all that is needed.

Table 4: SP35WO & WFRW: (a) Linear 'pec' vs. (b) Log 'lp.dB' Error Rate Representation

	SW = SP35WO: SP35turn w 1000ohm Write-Only i'face write C80 8,10,12,16v, then A,MAx80,160,320ipsx(11v.22-Nov-00,13v.28-Nov-00)																	
	2R = WFRW:																	
typec	C80 wv-trial	max.pec	pe.count	av14even	4	6	8	10	12	14	16	18	20	22	24	26	28	30
113	C80,8	516	SW pec	151	96	75	203	35	278	26	516	183	116	118	226	112	73	57
11	C80,10	57	SW pec	16	14	8	16	2	41	4	57	24	12	4	10	20	2	8
6	C80,12	26	SW pec	**9**	10	4	8	4	26	8	26	2	20	0	6	10	0	6
45	C80,16	181	SW pec	59	37	43	41	41	181	104	89	45	95	29	14	61	8	33
35	2C80,8v	85	2R pec	43	32	14	41		85	47	74	45	37	67	39	53	12	8
11	2C80,10v	81	2R pec	18	18	2	6	14	57	4	81	16	6	10	14	4	6	10
7	2C80,12v	36	2R pec	9	4	4	12	6	36	4	14	10	8	6	4	12	2	8
6	C80,12	26	SW pec	**9**	10	4	8	4	26	8	26	2	20	0	6	10	0	6
45	A80,11	112	SW pec	**51**	26	28	73	29	83	26	75	22	112	33	37	57	73	43
27	A80,13	95	SW pec	37	16	8	24	8	89	22	77	95	33	14	6	33	45	49
19	2A80,12	33	2R pec	21	24	18	33	24	32	12	28	14	6	16	12	24	29	18

	SW = SP35WO: SP35turn w 1000ohm Write-Only i'face write C80 8,10,12,16v, then A,MAx80,160,320ipsx(11v.22-Nov-00,13v.28-Nov-00)																	
	2R = WFRW:																	
typec	C80 wv-trial		lp dB	av14even	4	6	8	10	12	14	16	18	20	22	24	26	28	30
113	C80,8		SW lp.dB	21	20	19	23	16	24	14	27	23	21	21	24	21	19	18
11	C80,10		SW lp.dB	11	12	10	12	5	16	7	18	14	11	7	10	13	5	10
6	C80,12		SW lp.dB	**8**	10	7	10	7	14	10	14	5	13	0	8	10	0	8
45	C80,16		SW lp.dB	17	16	16	16	16	23	20	20	17	20	15	12	18	10	15
35	2C80,8v		2R lp.dB	16	15	12	16		19	17	19	17	16	18	16	17	11	10
11	2C80,10v		2R lp.dB	11	13	5	8	12	18	7	19	12	8	10	12	7	8	10
7	2C80,12v	best 2R	2R lp.dB	9	7	7	11	8	16	7	12	10	10	8	7	11	5	10
6	C80,12		SW lp.dB	**8**	10	7	10	7	14	10	14	5	13	0	8	10	0	8
45	A80,11		SW lp.dB	**17**	14	15	19	15	19	14	19	14	21	15	16	18	19	16
27	A80,13		SW lp.dB	14	12	10	14	10	20	14	19	20	15	12	8	15	17	17
19	2A80,12		2R lp.dB	13	14	12.8	15.3	14	15.2	11.1	14.6	11.8	8.45	12.3	11.1	14	14.8	12.8

Table 4 SP35WO & WFRW (a) Linear 'pec' and (b) Logarithmic 'lp.dB' Error-Rate Representation

In this table the 80 ips write-speed performance of SP35WO and WFRW are compared. Mode C performance as a function trial write-voltage is also compared performance of the corresponding even channels in mode A.

Table 4 is presented in two versions:

(a) is linear with pec entries (as previously defined), while
(b) is logarithmic with lp.dB(pec) = 10log(pec + 1) as entries.

Notes:

- 1 was added to pec in order to make lp.dB(0) = 0
- av.lp.dB < lp.dB(av.pec); also defined 'typical error count': typ.pec = $10^{av.lp.dB/10} - 1$ < av.pec
- As write-voltage was reduced from 12 to 10 volts in mode C, av.pec went from 9 and 9 to 16 and 18 for SP35WO and WFRW respectively, that is, only ~ doubled for both SP35WO and WFRW in mode C. This illustrates the usual weak dependence of error rate on moderate underdrive.
- Best 80 ips mode A performance was av.pec = 21 for WFRW at 12 volts. SP35WO's 80 ips mode A performance, av.pec = 37 and 51 at 13 and 11 volts respectively, was ~ 2 to 2.5 times worse than WFRW's.
- The 80 ips mode A to mode C av.pec ratio was ~ 2 for WFRW and at best ~ 4 for SP35WO. Thus there is some write-performance degradation due to active adjacent channels in mode A even at this low speed.
- This low-speed write-crosstalk effect of some sort has not been satisfactorily modeled.
- The 80 ips mode A effect on error rates was worse for SP35WO. This was in spite of (a) SP35's ½-inductance and (b) the much lower, < ¼ estimated, capacitive loading of WO- with respect to RW-interface.

Table 5: Logarithmic version of Table 2

SR = SP35RW Spin Physics 35-turn half-L shallow-gap TC w/ 1000ohm Read-or-Write I'face in Pos.1: 3-speed, 2-voltage write 29-Nov-00

resyncs	typec	h.m.s,v,vac	avpec	log.pec	av28\ch#	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	206	A80,11	262	SR lp.dB	23	17	22	17	27	22	25	24	26	23	24	21	27	25	28	22	24	24	23	20	28	20	26	20	23	22	27	19	19
		A80,13		SR lp.dB																													
#23	172	A160,11	226	SR lp.dB	22	21	22	20	27	23	27	21	28	23	27	19	27	27	24	23	23	23	25	22		19	22	19	21	19	23	15	14
	86	**A160,13**	**108**	**SR lp.dB**	**19**	13	18	16	22	20	21	20	21	24	19	21	22	20	22	20	20	22	19	16	25	16	18	25	18	19	19	15	14
	296	A320,11	443	SR lp.dB	25	23	23	22	28	28	30	20	29	24	30	21	28	29	28	28	25	25	28	26	33	22	21	22	26	21	23	15	14
#14	245	**A320,13**	**306**	**SR lp.dB**	**24**	18	21	19	26	24	25	23	27	23	26		28	26	26	24	26	26	24	22	28	22	24	24	21	25	30	18	20

resyncs	typec	even.ran.mA	avpec	log.pec	av14even	4	6	8	10	12	14	16	18	20	22	24	26	28	30
	100	erm80,11	122	SR lp.dB	20.0	18	15	22	22	22	20	24	24	21	21	18	16	21	15
		erm80,13		SR lp.dB															
	102	erm160,11	144	SR lp.dB	20.1	20	21	24	19	23	19	26	25	21	23	17	15	14	15
#18	76	**erm160,13**	**106**	**SR lp.dB**	**18.9**	12	14	19	20	20	22	22		18	14	15	25	23	20
#18	216	erm320,11	331	SR lp.dB	23.4	21	25	29	22	26	23	31		26	26	21	20	19	14
	75	**erm320,13**	**96**	**SR lp.dB**	**18.8**	17	13	23	16	21	21	24	21	18	20	19	19	19	13

resyncs	typec	odd.ones.mA	avpec	log.pec	av14odd	5	7	9	11	13	15	17	19	21	23	25	27	29	31
	3	o1m80,11	7	SR lp.dB	6.5	0	0	5	10	12	7	8	8	7	16	8	10	0	0
		o1m80,13		SR lp.dB															
#23	2	o1m160,11	6	SR lp.dB	4.3	0	17	0	7	0	7	0	7	10		0	8	0	0
#17	1	**o1m160,13**	**1**	**SR lp.dB**	**2.0**	0	0	5	5	0	5		0	0	7	0	5	0	0
#17,23	2	o1m320,11	11	SR lp.dB	4.8	0	0	0	0	10	0		7	20		10	11	0	0
	2	**o1m320,13**	**4**	**SR lp.dB**	**4.3**	7	15	7	7	0	5	0	7	0	5	0	8	0	0

SW = SP35WO: SP35turn w 1000ohm Write-Only i'face write C80 8,10,12,16v, then A,MA 80,160,320ips (11v.22-Nov-00,13v.28-Nov-00)

lp dB 10*log(pe+1) logarithmic error rate FOM, adjusted to make best case averages approach zero asymptotically

contras	typec	h.m.s,v,vac		log.pec	av28\ch#	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
w/r 11v	53	A80,11		SW lp.dB	**17**	14	18	15	17	19	23	15	13	19	19	14	17	19	19	14	19	21	15	15	14	16	19	18	21	19	18	16	20
19 of 28	35	A80,13		SW lp.dB	16	12	14	10	15	14	17	10	12	20	20	14	15	19	29	20	18	15	12	12	14	8	14	15	22	17	19	17	14
w/r 11v	24	A160,11		SW lp.dB	**14**	16	14	10	13	16	19	10	12	18	22	13	15	16	19	12	12	15	14	10	20	8	13	14	12	12	17	11	7
6 of 28	37	A160,13		SW lp.dB	16	10	14	14	15	15	20	16	11	21	19	16	15	19	23	19	17	14	16	13	14	10	16	14	16	14	22	16	14
3 of 28	79	A320,11		SW lp.dB	19	14	21	8	17	23	27	11	19	24	24	18	20	27	25	15	18	22	20	15	23	19	18	16	18	26	20	15	10
w/r 13v	40	A320,13		SW lp.dB	**16**	10	19	7	16	22	23	8	16	22	18	16	20	19	19	15	21	20	19	12	21	13	15	14	20	19	13	0	12

resyncs	typec	even.ran.mA		log.pec	av14even	4	6	8	10	12	14	16	18	20	22	24	26	28	30
	9	erm80,11		SW lp.dB	10	5	10	13	0	18	5	17	25	5	10	5	8	13	7
#18	8	erm80,13		SW lp.dB	**9**	10	5	13	5	21	7	17		8	8	0	10	10	10
	5	erm160,11		SW lp.dB	8	5	5	8	5	14	11	14	10	5	10	5	10	5	0
#18	5	erm160,13		SW lp.dB	**8**	7	8	11	8	11	11	8		11	0	0	7	7	7
	157	erm320,11		SW lp.dB	22	19	10	30	14	29	22	30	15	31	12	32	14	36	13
#18	9	erm320,13		SW lp.dB	**10**	15	5	15	10	7	17	14		11	12	5	8	10	0

	typec	odd.ones.mA		log.pec	av14odd	5	7	9	11	13	15	17	19	21	23	25	27	29	31
	0	o1m80,11		SW lp.dB	1	0	0	0	5	0	0	5	0	5	0	0	0	0	0
	0	o1m80,13		SW lp.dB	1	0	0	0	0	0	0	8	0	0	0	0	0	0	0
	0	o1m160,11		SW lp.dB	1	0	0	0	0	0	0	0	0	0	0	8	0	0	0
	0	o1m160,13		SW lp.dB	1	0	0	0	0	0	0	0	5	0	5	0	5	0	0
	2	o1m320,11		SW lp.dB	5	0	5	5	5	11	13	5	0	0	7	7	8	5	0
	0	o1m320,13		SW lp.dB	**1**	0	0	5	0	0	0	0	0	0	8	0	0	0	0

Table 5 Logarithmic version of Table 2 and Suggestions for Improved Display

Logarithmic error rate representation allows for more compact presentation of many-channel data. Note lp.dB < 28 to nearest integer is equivalent to the pec < 600 performance specification. However, as is evident, Table 5 does little to improve upon Table 2 in terms of making problem channels more noticeable.

An even more compact one-character logarithmic performance-monitoring representation is here suggested:

Let l2.pec = $\log_2$(pec + 1) in hexadecimal, to the nearest integer.

The numeric integer values of l2.pec, 0 through 9, would then indicate perfect through barely in-spec performance with adequate, octave, resolution.

A through F would strikingly indicate 6 more octaves of out-of-spec performance, that is, pec's from 2^{10} to 2^{15} (PER to ~ 3×10^{-2}).

Such high error rates do not usually prevent VLBI processing or 'use' of the data, especially if, as is often the case, the sync-loss rate is not also greatly increased.

It is important for diagnostic purposes therefore that sync-losses, that is, one or more bit-slips or 'resyncs' counted during a finite data-length (usually million byte) parity error count, also be flagrantly co-indicated. Suggested is substitution of non-hex characters for resync-invalidated l2.pec entries -- for example, the character-set {X, Y, Z }for {1, 2 to 4, more than 4} resyncs per 400 frames (million bytes).

In any case, background-color coding of entries, similar to that used in these tables, clearly aids and encourages a human inspector/diagnostician of logged performance data.

I would therefore also advocate the careful use of color in future video and printed displays of performance-monitoring logs.

Table 6: WFRW and WFWO: ANALOG PERFORMANCE MEASURES

WFRW	SNR dB		av28\ch#	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2A80,12v,10"	2.2 snr		18.7	18.9	19.1	18.7	18.4	19.4	18.5	19.0	19.0	18.1	18.4	18.0	18.6	17.8	19.4	18.8	18.9	18.8	18.7	19.0	18.7	19.0	18.7	19.1	18.7	19.0	17.3	19.2	18.1
2A160,12v,10"	2.2 snr		19.1	19.3	19.6	19.2	19.1	19.6	19.2	19.0	19.4	18.5	18.7	19.2	19.0	18.4	18.8	19.0	19.4	19.7	19.2	18.9	19.3	19.0	18.3	19.4	19.0	20.2	17.5	19.6	19.3
2A320,12v,10"	2.2 snr		19.1	19.7	19.9	19.4	19.1	19.9	19.3	19.3	18.6	17.7	18.9	18.9	19.2	18.7	19.0	19.2	19.3	19.8	19.1	19.2	19.0	17.7	18.4	19.1	19.3	19.3	18.0	19.2	19.5
WFWO	SNR dB		av28\ch#	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1A80,8v,9"	2.2 snr		18.0	18.3	17.6	18.6	18.5	18.0	17.4	18.4	18.3	16.5	17.4	16.9	17.8	17.4	19.0	17.8	17.9	17.7	17.8	18.3	17.7	17.7	18.3	18.8	18.2	19.3	16.2	18.7	18.2
1A160,8v,9"	2.2 snr		18.5	18.6	18.0	18.8	19.0	19.1	18.1	18.6	18.9	17.5	18.1	17.8	18.7	17.4	18.2	18.2	18.8	18.4	18.2	18.6	17.9	18.4	18.5	18.9	18.7	19.6	18.6	18.6	18.6
1A320,8v,9"	2.2 snr		16.9	17.5	17.0	17.6	17.5	17.3	17.4	17.5	17.9	15.5	16.5	16.4	17.4	16.1	14.7	16.7	17.6	17.2	16.7	17.0	16.8	16.6	17.0	16.9	17.2	18.2	15.3	17.8	17.0
1A320,8v,12"	2.2 snr		17.2	17.5	17.3	17.5	18.0	17.9	17.0	17.6	18.2	15.7	17.0	17.4	18.1	16.3	14.0	17.3	18.1	17.3	16.7	17.4	17.1	16.8	17.5	17.1	17.8	19.0	15.7	17.6	17.5
1A320,10v,12"	2.2 snr		18.3	17.9	18.5	18.8	18.7	19.0	18.2	18.8	19.1	16.9	17.8	18.6	18.9	17.2	14.1	18.5	19.1	19.1	18.5	18.7	18.2	18.1	18.4	18.6	18.5	19.5	16.4	18.9	18.2
WFRW	S/WX dB	min s/wx	av14odd		5		7		9		11		13		15		17		19		21		23		25		27		29		31
2X80,12v,10"	2.2 s/wx	11.2	12.2		12.4		12.1		11.3		11.2		12.1		12.0		12.3		12.1		12.5		12.6		12.2		12.2		12.3		13.1
2X160,12v,10"	2.2 s/wx	9.4	10.2		9.6		10.1		9.9		9.6		9.6		9.5		9.4		10.3		10.3		11.2		10.0		10.4		10.6		12.9
2X320,12v,10"	2.2 s/wx	5.3	6.9		6.6		6.3		6.9		5.3		6.9		6.7		6.1		6.7		6.7		7.3		6.5		7.4		7.2		9.6
WFWO	S/WX dB	min s/wx	av14odd		5		7		9		11		13		15		17		19		21		23		25		27		29		31
1X80,8v,9"	2.2 s/wx	12.0	12.9		13.4		12.9		12.9		12.6		12.9		12.8		14.1		12.0		13.2		12.4		12.4		13.0		12.1		13.7
1X160,8v,9"	2.2 s/wx	9.9	11.8		12.0		11.5		11.9		11.9		11.4		12.6		9.9		10.8		12.4		10.9		12.3		11.8		13.4		12.5
1X320,8v,9"	2.2 s/wx	4.8	8.6		8.3		8.3		8.4		8.8		7.6		8.3		4.8		8.9		8.8		9.7		9.2		9.6		8.8		10.7
WFRW	A-MA dB	maxabs	av14even	4		6		8		10		12		14		16		18		20		22		24		26		28		30	
2M80,12v,10"	2.2 a-ma	0.5	0.1	0.5		0.0		0.4		0.2		-0.1		0.1		-0.2		0.1		-0.1		0.1		0.2		0.3		0.0		0.1	
2M160,12v,10"	2.2 a-ma	0.6	0.1	0.1		0.0		0.1		0.0		-0.2		0.4		-0.5		0.4		0.2		-0.2		0.6		0.0		0.6		0.3	
2M320,12v,10"	2.2 a-ma	1.0	0.0	0.4		0.3		0.5		-0.1		-0.3		-0.3		0.5		1.0		-0.1		-0.1		-0.3		0.1		-1.0		-0.5	
WFWO	A-MA dB		av14even	4		6		8		10		12		14		16		18		20		22		24		26		28		30	
1M80,8v,9"	2.2 a-ma	0.8	-0.2	-0.1		-0.2		-0.4		-0.4		-0.8		-0.3		-0.1		0.1		-0.4		0.0		-0.6		0.0		0.3		0.2	
1M160,8v,9"	2.2 a-ma	0.7	0.3	0.4		0.6		0.4		0.3		0.1		0.5		0.4		0.7		0.1		0.1		0.5		0.2		0.0		0.2	
1M320,8v,9"	2.2 a-ma	0.6	0.1	0.2		0.6		-0.2		0.0		0.0		-0.5		0.1		0.4		0.4		0.1		0.1		-0.1		-0.1		0.3	
WFRW	dB/(1/2-MHz)		av28\ch#	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2A80,12v,10"	slope		-4.9	-5.3	-4.9	-4.9	-5.5	-5.2	-5.5	-5.0	-4.6	-4.9	-4.9	-5.1	-4.6	-5.1	-3.5	-4.9	-4.8	-4.9	-4.7	-5.0	-5.1	-4.9	-4.8	-4.6	-5.2	-5.0	-5.2	-4.9	-5.0
2A160,12v,10"	slope		-4.7	-4.9	-5.0	-5.1	-4.9	-4.9	-4.9	-4.8	-4.5	-4.6	-4.5	-4.5	-4.4	-4.6	-4.3	-5.1	-4.8	-4.3	-4.6	-4.8	-4.6	-4.7	-4.9	-4.7	-4.9	-4.5	-4.9	-4.6	-4.7
2A320,12v,10"	slope		-4.8	-4.9	-4.9	-4.9	-5.1	-4.7	-5.0	-5.0	-5.0	-5.0	-4.6	-4.8	-4.4	-4.4	-4.4	-4.7	-4.6	-4.0	-4.9	-4.8	-4.9	-5.2	-4.7	-4.6	-4.9	-4.9	-5.6	-4.8	-4.7
WFWO	dB/(1/2-MHz)		av28\ch#	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1A80,8v,9"	slope		-4.4	-4.3	-4.4	-4.5	-4.8	-4.4	-5.0	-4.6	-4.3	-4.3	-4.5	-5.0	-4.4	-4.2	-3.3	-4.7	-4.5	-4.1	-4.6	-4.0	-4.5	-4.3	-4.3	-4.2	-4.4	-4.4	-4.7	-4.4	-4.8
1A160,8v,9"	slope		-4.1	-4.6	-4.2	-4.1	-4.2	-3.9	-4.8	-4.1	-3.8	-4.0	-4.1	-4.1	-3.9	-4.1	-3.9	-4.2	-4.1	-3.7	-4.3	-3.9	-4.1	-3.9	-4.2	-3.7	-4.3	-4.2	-4.0	-4.0	-4.2
1A320,8v,9"	slope		-4.0	-4.4	-4.1	-4.2	-3.9	-3.6	-4.3	-4.1	-3.7	-4.4	-4.4	-3.7	-3.9	-4.0	-5.2	-3.9	-4.0	-3.6	-3.9	-3.8	-4.1	-4.2	-4.1	-3.8	-4.3	-3.7	-4.4	-3.9	-4.2
1A320,8v,12"	slope		-4.2	-4.4	-4.2	-4.1	-4.3	-4.1	-4.4	-4.2	-3.8	-4.5	-4.1	-3.8	-4.0	-4.2	-6.1	-3.9	-4.3	-3.9	-4.5	-3.7	-4.1	-4.4	-4.1	-3.8	-4.3	-3.7	-4.4	-4.1	-4.0
1A320,10v,12"	slope		-4.3	-4.6	-4.2	-4.1	-4.7	-3.9	-4.8	-4.4	-3.9	-4.8	-4.2	-3.8	-4.1	-4.5	-6.5	-4.1	-4.5	-3.8	-4.2	-4.1	-4.2	-4.4	-4.2	-4.0	-4.3	-4.1	-4.8	-4.0	-4.5
WFRW	dB/(1/2-MHz)^2		av28\ch#	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2A80,12v,10"	curvature		-1.1	-1.5	-1.4	-0.7	-1.0	-2.2	-1.1	-1.1	-1.3	-0.7	-1.5	-0.7	-0.7	-0.9	-1.6	-1.1	-1.6	-1.4	-0.8	-0.6	-0.8	-1.0	-1.2	-1.6	-0.6	-1.6	-0.9	-0.9	-1.0
2A160,12v,10"	curvature		-1.1	-1.6	-1.4	-0.3	-0.5	-2.0	-0.8	-0.7	-1.2	-1.1	-1.3	-1.2	-0.8	-0.7	-1.3	-1.5	-1.8	-1.8	-1.3	-0.3	-1.1	-1.2	-1.0	-1.4	-1.1	-1.7	-0.9	-1.3	-1.0
2A320,12v,10"	curvature		-1.0	-1.6	-1.8	-0.5	-0.4	-1.5	-1.1	-1.1	-0.8	-0.1	-1.4	-0.8	-1.0	-1.1	-0.6	-1.0	-1.4	-1.7	-1.4	-0.3	-1.0	-0.1	-1.3	-0.9	-1.3	-1.4	-0.5	-0.4	-0.9
WFWO	dB/(1/2-MHz)^2		av28\ch#	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1A80,8v,9"	curvature		-0.9	-1.3	-1.1	-0.8	-1.0	-0.6	-1.0	-1.3	-1.4	-0.4	-1.0	-0.3	-0.9	-0.9	-2.0	-0.6	-1.3	-1.1	-1.0	0.0	-1.0	-0.3	-1.3	-1.1	-1.0	-1.5	-0.6	-1.2	-0.9
1A160,8v,9"	curvature		-1.0	-1.5	-1.1	-0.6	-0.6	-1.3	-1.2	-0.8	-1.1	-0.8	-1.6	-1.1	-1.1	-0.7	-0.6	-1.3	-1.6	-1.4	-0.9	-0.1	-0.7	-0.8	-0.9	-1.2	-1.3	-1.3	-0.8	-0.6	-0.9
1A320,8v,9"	curvature		-0.6	-0.6	-0.9	-0.8	-0.3	-1.0	-1.2	-1.2	-1.3	-0.4	-1.1	-0.3	-1.0	-0.8	1.3	-0.4	-1.4	-0.9	-0.4	0.0	-0.8	0.1	-0.9	-0.1	-0.4	-0.6	-0.3	-1.2	-0.1
1A320,8v,12"	curvature		-0.7	-0.8	-1.1	-0.5	-0.7	-1.0	-0.4	-0.8	-1.5	0.3	-1.1	-1.3	-1.3	-0.4	1.6	-1.3	-2.0	-1.2	-0.2	-0.1	-0.7	-0.4	-1.3	-0.9	-0.7	-1.4	-0.7	-0.6	-0.4
1A320,10v,12"	curvature		-0.8	-0.7	-1.4	-0.9	-0.6	-1.0	-1.3	-0.8	-1.0	-0.4	-0.7	-1.0	-1.1	-0.6	2.1	-1.1	-2.0	-1.6	-0.7	-0.1	-1.2	-0.3	-1.3	-0.8	-1.1	-1.5	-0.5	-1.1	-0.6

Table 6 WFRW & WFWO Analog Performance Measures

Table 6 lists five derived analog measures of performance for each test of WFRW and WFWO for every tested channel.

These measures are:

1. bandedge SNR in dB, actually by VLBI head-test convention at 2.2 MHz (44/45th bandedge)
2. bandedge S/WX in dB at 2.2 MHz
3. bandedge modes A-MA in dB at 2.2 MHz, a ‘null’ sanity check,
4. Slope of snr-spectrum in dB/(.5MHz) at 2.2 MHz, derived from markers at 1.5 and 2.5 MHz, and
5. Curvature of snr-spectrum in dB/(.5MHz)^2 at 2.2 MHz, from markers at 1.5, 2.0, 2.5 MHz.

These 3 marker frequencies were chosen for the raw-data sets to be midway between parity pips in order ensure that the raw spectral power measurements contain only random noise and ideally reflect only incoherent interference effects of independent random data in all channels.

SNR, S/WX, and A-MA were derived by quadratic interpolation to 2.2 MHz.

Spectral power in a 4th marker at the 2.25 MHz bandedge was also logged and additional measures of coherent power and crosstalk were derived, as discussed under and shown only in Table 7.

All signal, S, spectral raw data points were first converted to signal-to-electronic-noise points, S/EN by subtracting an EN data-set obtained with the ‘reading’WF drive stationary ‘looking at’ WFRW through the 80 ips equalizer.

All spectral points were manually entered into Excel spreadsheets for mathematical manipulations and display. Every SNR, S/WX, and A-MA point in Tables 6 and 7 has associated with it 4 raw marker-power entries.

A printed full-spectrum plot, including marker table, is associated with each point. This large (saved) collection of printed spectra was used for clues to help explain unusual channel behavior.

SNR

For WFRW’s own recordings, bandedge SNR (remember all performance measurements in this memo use WFRW reading at 80 ips) was reasonably high, quite consistent, and virtually independent of write-speed from 80 through 320 ips:

Identical average SNR of 19.1 dB at 160 and 320 ips, and hardly significantly lower 18.7 dB at 80 ips, was observed. Remember that WFRW uses a standard-inductance deep-gap Metrum triple-cap, which, in conjunction with the high-capacitance RW-interface, resonates with low Q only slightly above the 9 MHz 320 ips bandedge.

Best-minus-worst SNR was 1.4, 1.9, and 2.2 dB at 80, 160, and 320 ips write-speed respectively, a very low spread that grows only slightly with write-speed. Best and worst are also different channels at each speed, as might be expected with such a low and speed-independent spread.

Worst pec’s of 75, 75, and 274 were observed in channels # 17, # 19, and # 15 at 80, 160, and 320 ips write-speed respectively. But the corresponding 19.4, 19.4, and 19.2 dB worst-pec-channel SNRs were all 0.3 to 0.5 dB above, not below, average. Furthermore, channel # 12 with worst SNR of 17.7 dB, 1.0 dB below average, at 320 ips write-speed, had pec = 63, better than av.pec = 102 for that case.

For WFRW there was no significant dependence of SNR on write-speed. And, over a small ~ +/- 1 dB spread of SNR, no correlation between error rate and SNR. Thus SNR variations cannot explain the ~ 3-fold increase in error-rate that occured when write-speed was increased from 160 or 80 to 320 ips.

For WFWO’s recordings, bandedge SNR was lower on average by 0.7 dB than for WFRW, much less consistent from channel to channel, but also virtually independent of write-speed through 320 ips:

Average SNR was 18.3, 18.5, and 18.0 dB at 320, 160, and 80 ips respectively. Remember that WFWO uses a standard-inductance, but heavily worn, hence shallow-gap, Metrum stepped headstack.

Best-minus-worst SNR was 5.1, 2.2, and 3.1 dB at 320, 160, and 80 ips write-speed. Channel # 28 was consistently best with 19.5, 19.6, and 19.3 dB SNR respectively. Worst SNRs of 14.1, 17.2, and 16.2 dB were observed in # 17, # 16, and # 29 at 320, 160, and 80 ips.

In spite of WFWO’s 0.7 dB lower average ‘written’ SNR and the only 14.1 dB worst case for # 17 at 320 ips, WFWO’s av.pec and max.pec performance at all speeds was slightly better than WFRW’s: WFRW/WFWO error-rate ratios were ~ 1.5 as Table 1 shows.

The worst-case SNR 14.1 dB channel # 17 at 320 ips had pec = 16. Thus, surprisingly, # 17 at 320 ips was one of 4 best digital-performance channels. Worst-SNR channels at 160 and 80 ips, # 16 with pec = 16 and # 29 with pec = 33, had ~ av.pec and ~ 2 times av.pec respectively.

Again, for WFWO there no clear dependence of SNR on speed (# 17 is a notable exception) nor of error-rate on SNR over the large 6 dB range down to 14 dB.

Anecdotally, this is not the first time that I have observed error rates of $<\sim 10^{-5}$ with bandedge SNR as low as 14 dB in 80 ips playback (another instance is mentioned in memo #285).

However, the write and read conditions necessary to assure a low error-rate in spite of low-SNR have not been quantified. The combination of various forms of interference needs to be kept below some as yet ill-defined threshold.

It should be noted that #17 at 320 ips had not only the lowest SNR but also the lowest S/WX = 4.8 dB. Thus in spite of low SNR and very high write-crosstalk # 17 yielded reasonably low error-rate. For reasons that remain far from clear, #17 does incur a large 4.3 dB write-SNR loss with write-speed increase from 80 to 320 ips, and a smaller 1.2 dB loss from 80 to 160 ips.

Systematically high error-rates, on the other hand, were observed in the case of SP35RW in spite of substantially less write-crosstalk and in spite of higher SNR (see discussion of Table 7). This suggests that avoidance of Non-Linear Transition-Shift, NLTS, a form of write-side inter-symbol interference, may be a larger part of the problem in SP heads than write-crosstalk, a write-side form of adjacent-channel interference.

NLTS is in general caused by overdrive. The write-voltage threshold at which NLTS becomes significant is proportional to head-efficiency. Efficiency is itself channel, wavelength, and frequency-dependent. The write-voltage threshold is also inversely proportional to the head+interface write-voltage-to-head-current transfer-function. The greater the combined variation of efficiency over channels, wavelengths, and speed or frequency, the more difficult it becomes to avoid NLTS even though it can usually be reduced by lowering write-voltage. With some standard SP, but never with Metrum, headstacks this has usually been at the expense of 1 – 3 dB of bandedge SNR (see memo # 285).

S/WX

Average S/WX for WFRW, WFWO was 6.9, 8.6 dB at 320 ips; 10.2, 11.8 dB at 160 ips; and 12.2, 12.9 dB at 80 ips write-speed.

The differences, WFWO-WFRW, favored WFWO by 1.7, 0.6, and 0.7 dB at 320, 160, and 80 ips respectively, most significantly at 320 ips. Average digital performance favored WFWO slightly, like average S/WX, but unlike average SNR which slightly favored WFRW.

Write-crosstalk increased qualitatively as expected with write-speed: 2.0, 1.1 dB from 80 to 160 ips; 5.3, 4.3 dB from 80 to 320 ips, for WFRW, WFWO respectively. The increase in average write-crosstalk from 160 to 320 ips was ~ 3.3 dB for both WFRW and WFWO. For both, the significant increase in average write-crosstalk at 320 ips seems closely related to the 3 to 5-fold increase in av.pec observed in going from 160 to 320 ips write-speed.

For WFRW, worst S/WX = 5.2 dB for # 11 at 320 ips produced better than average pec = 93. The surprisingly low pec = 16 for #17 of WFWO with S/WX <~ 4.8 dB, has already been mentioned.

A-MA

This measure is the difference, only for even-numbered channels, between mode A and mode MA data. The measure of S/WX above is the same kind of difference, only for odd-numbered channels which are 'ones' in MA. The random even MA channels should have their spectra affected only possibly by adjacent coherent 'ones' channels, and, if so, only at bandedge (within the 30 KHz resolution bandwidth used). Thus, A-MA (evaluated at 2.2 MHz based on quadratic fit to points at 1.5, 2.0, and 2.5 MHz, which are all 0.25 MHz distant from the nearest parity pips including bandedge) should be zero to within measurement and repeatability errors.

The 0.3 dB average absolute and 1.0 dB maximum absolute A-MA differences do not seem significant. Thus, this null 'sanity' check seems OK.

Slope and Curvature

The 28-channel averages of both spectrum slope and curvature showed no clear trend with speed for either WFRW or WFWO.

But WFWO #17 showed anomalous behavior:

It had a low –3.3 slope at 80 ips and high –6.5 dB/(.5MHz) slope at 320 ips, compared to the –4.4 speed-independent average slope.

It also had -2.0 curvature at 80 ips and high positive +2.1 dB/$(.5\text{MHz})^2$ curvature at 320 ips, compared to the –0.9 speed-independent average curvature. I note that only WFWO's #17 only at 320 ips showed positive curvature, and did so under all 3 conditions tested, 8v-9", 8v-12", and 10v-12".

Table 7: SP35RW and SP35WO Analog Performance Measures

4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	av28\ch#	2.2 MHz SNR cB	av28\ch#	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
5	9	3	0	6	-2	4	11	-9	-2	-9	2	-10	6	-7	3	1	-3	1	-2	1	-3	-2	0	7	-22	6	5	190	A80,11	185	7	8	5	-1	8	-7	4	5	-12	-8	0	2	-10	-7	-1	5	5	-1	2	-2	-2	2	-4	0	8	-17	3	10
																													A80,13	191	1	6	3	4	11	-5	3	8	-13	-3	-3	-2	-11	9	-4	1	4	-1	-3	-2	0	-1	-4	9	6	-17	0	3
5	9	9	-1	8	0	-1	2	-10	-5	0	-4	-7	-9	-1	4	2	2	0	-6	2	-7	1	-1	8	-12	5	5	192	A160,11	186	5	3	3	0	1	-7	2	5	-15	2	3	1	-9	-7	-4	5	10	0	-1	1	-4	-2	0	1	6	-18	6	13
4	8	8	1	9	4	-3	4	-10	1	-7	-1	-4	-5	-2	1	0	1	1	0	6	-4	3	-9	7	-13	1	0	189	A160,13	189	1	7	0	1	6	-4	4	7	-15	-4	1	2	-12	-8	-4	3	6	1	3	-2	5	-1	1	-1	10	-22	3	11
4	10	7	1	1	0	-3	6	-19	-3	-4	3	5	-4	-2	7	6	-3	-3	1	4	-2	0	0	8	-13	-9	2	192	A320,11	183	7	8	2	6	9	-5	1	9	-21	-3	6	1	1	-5	-2	5	7	-2	-4	-4	0	-4	-12	-3	4	-10	1	6
6	7	4	3	10	-1	-1	4	-12	1	-6	-1	-5	-3	2	6	5	4	2	3	0	1	-1	-4	8	-15	-17	-1	189	A320,13	190	-1	12	5	4	9	0	8	10	-16	-1	2	4	-6	-1	-2	3	5	-5	-1	1	0	-3	2	-3	5	-17	-18	3

5	7	9	11	13	15	17	19	21	23	25	27	29	31	av14odd	2.2 MHz S/WX cB	av14odd	5	7	9	11	13	15	17	19	21	23	25	27	29	31
-5	-10	-2	-7	2	-7	0	-3	4	3	4	12	-9	18	135	X80,11	134	-3	-3	-10	5	-19	5	-19	-3	7	7	10	11	0	11
															X80,13	134	-10	0	-17	6	-20	4	-8	-14	10	8	9	28	-4	8
-4	-11	2	-7	-6	-13	-13	-1	9	0	1	15	5	25	121	X160,11	136	-23	5	-14	17	-16	9	-16	9	-10	13	-1	11	-3	18
-5	-8	6	-9	5	-12	-13	-7	7	6	1	9	0	21	116	X160,13	115	-13	5	-21	0	-23	5	-25	-12	14	7	15	17	8	24
-2	-5	0	-3	1	-14	-6	-2	-9	3	-2	5	7	26	95	X320,11	108	-12	10	-13	12	-9	-1	-13	2	-9	6	-5	10	1	20
-23	1	-14	5	-7	-4	-5	7	-5	2	0	7	6	30	123	X320,13	105	-6	-9	-4	-13	-11	-15	-2	6	-6	15	-5	14	6	29

4	6	8	10	12	14	16	18	20	22	24	26	28	30	av14even	2.2 MHz A-MA cB	av14even	4	6	8	10	12	14	16	18	20	22	24	26	28	30
2	-1	-4	3	3	-3	-3	-1	0	1	0	1	2	0	-1	M80,11	0	2	-2	5	-3	-2	-3	5	4	-3	2	-5	0	2	-2
															M80,13	-1	-1	0	1	0	-1	0	4	9	1	-2	-2	0	-4	-4
1	2	1	-1	0	0	-3	5	1	-1	-1	1	-3	-2	2	m160,11	0	-2	-3	-2	-3	-6	0	4	0	3	-2	-4	7	2	5
5	3	4	0	-2	0	2	3	-4	-4	1	3	-3	-7	1	M160,13	-1	0	-1	-3	1	-4	2	-6	10	-2	2	1	2	-1	-2
5	1	-6	-8	-2	-5	4	7	1	-3	2	2	-2	3	0	M320,11	2	2	-1	4	-5	-1	0	5	2	2	-9	6	-6	3	-1
8	-4	-1	-5	0	-4	-3	2	4	0	-3	-8	2	11	4	M320,13	2	1	2	-2	1	3	-4	-1	8	-2	0	-3	2	-3	-2

4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	av28\ch#	slope cB/.5MHz	av28\ch#	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1	1	-1	1	3	-2	-4	7	-1	1	-5	3	0	10	-1	-2	-1	0	2	0	0	-1	-1	-5	1	-3	2	-3	-46	A80,11	-44	3	1	-1	0	3	-4	-4	0	0	0	-3	2	0	1	3	-6	6	1	4	-1	-1	1	2	-3	1	-3	0	-2
																													A80,13	-44	-1	-1	-2	0	2	-4	0	5	0	1	-4	0	-1	13	0	-3	2	0	-1	0	-1	0	-2	6	0	-5	-2	-3
2	1	4	-2	3	0	-6	1	1	1	-3	0	4	2	-1	-2	2	0	2	-2	3	-2	-1	-3	0	-3	0	2	-44	A160,11	-41	-1	2	3	-2	1	-3	3	5	-1	2	0	2	1	0	1	-5	3	4	1	4	-1	-3	1	-7	-2	-3	-1	-2
-2	0	-1	1	2	-1	-3	3	-1	5	-3	0	3	0	-1	0	-1	0	1	1	1	0	4	-8	0	-2	-1	1	-49	A160,13	-44	-2	2	1	-3	0	-3	-1	5	1	1	0	4	0	3	1	-1	0	0	1	-1	2	-2	0	-7	0	-6	0	-2
0	3	1	-2	-1	-1	-5	3	-5	0	-2	4	8	4	-1	0	1	-2	1	2	2	4	-1	-6	0	-3	-9	1	-44	A320,11	-41	0	0	1	1	1	-4	-3	3	-2	2	2	-1	14	0	0	2	3	-1	-2	-2	0	-5	-1	-7	4	-2	-1	-3
-2	-1	-2	0	3	-1	2	4	-5	2	1	4	4	1	2	-1	2	-1	2	4	-1	-1	2	-7	1	-2	-13	-2	-49	A320,13	-44	1	0	0	-1	3	-2	-1	3	-2	3	3	3	1	2	1	1	2	-1	1	2	4	0	4	-5	3	-3	-11	-5

4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	av28\ch#	curv cB/(.5MHz)^2	av28\ch#	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	-6	2	4	-3	-1	-2	-3	-2	-1	8	0	5	-7	-2	-10	-5	2	3	-3	4	0	1	2	0	7	4	-1	-9	A80,11	-10	-5	-7	0	5	-4	2	0	-1	4	3	5	0	1	1	-6	-6	-2	2	10	-6	3	1	1	0	-2	2	-1	1
																													A80,13	-10	-1	-2	3	2	-8	3	1	-6	5	-1	4	1	3	-8	-2	-1	-2	0	11	-2	1	0	1	-13	-1	3	-1	6
-5	-2	-3	3	0	-2	-3	1	-2	-1	3	6	2	4	1	-8	-1	-5	9	1	4	5	-3	-1	-3	2	-2	0	-11	A160,11	-9	-5	0	4	2	-3	-1	2	-5	4	-8	2	3	1	0	-1	-2	-6	3	9	-4	-1	2	-4	2	-3	2	-2	2
-1	0	1	5	-4	-4	-2	-3	-2	-4	-1	-1	1	1	-3	-4	-5	-3	7	2	3	2	-1	1	-1	3	4	6	-10	A160,13	-10	-2	-3	5	5	-1	0	-1	-1	5	-3	0	-2	6	5	-4	-4	-4	-3	6	0	-2	2	-5	-1	-6	7	0	1
1	-6	2	2	-1	-1	6	-4	3	0	4	2	-7	5	1	-6	-11	2	9	-6	-1	2	-3	-1	-3	-4	8	8	-9	A320,11	-11	-2	-5	6	-2	-6	-1	-3	-5	7	4	-2	3	-3	3	-6	-1	-5	6	12	-1	-5	0	4	3	-4	-1	-2	4
-7	-4	5	1	-6	1	4	-1	0	-3	2	2	3	-1	-5	-6	-8	-3	6	3	3	-6	6	-2	0	4	11	8	-10	A320,13	-10	2	-6	1	1	-4	-2	-2	-6	6	-6	0	-2	3	-4	0	-3	-2	6	6	-3	2	-2	-4	0	3	7	17	-1

4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	av28\ch#	BEpip/ran cB	av28\ch#	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
-6	2	0	2	5	2	1	-3	1	0	-1	-3	-2	6	1	-2	3	-3	-1	-3	3	-5	1	1	-5	5	-1	1	35	A80,11	38	-9	-2	-4	8	-10	0	7	9	5	4	-7	9	-3	-4	-8	8	4	1	-4	6	2	-5	-8	11	-5	-5	-1	2
																													A80,13	36	2	5	-10	-1	-5	-2	-3	-4	1	-1	-10	-2	-4	10	0	1	2	4	1	1	-2	-2	-1	21	-4	5	-3	1
0	-2	-8	3	-4	-3	6	3	-1	6	0	8	-3	3	2	-4	1	1	-2	-4	2	2	-9	5	-1	1	-6	5	35	A160,11	37	-4	3	-4	1	0	0	1	-4	4	-8	1	-1	-4	4	0	1	8	5	4	-1	5	0	-9	-2	-5	2	0	3
-1	4	-7	6	-3	2	-4	4	3	-1	-2	-1	-3	0	-7	-4	-1	-3	0	2	1	1	1	2	-1	2	5	5	35	A160,13	36	2	2	-2	4	-6	1	1	-1	6	0	-2	-4	2	6	6	-10	5	5	-2	-2	-1	3	-6	-2	-7	4	0	-2
1	0	-3	-1	9	3	8	-6	4	6	7	-2	5	0	6	-8	-4	-6	-1	4	-8	0	-9	-6	-4	5	-1	2	36	A320,11	36	-7	-2	-7	-4	-6	1	-3	-6	0	3	7	-4	16	-3	-5	3	-7	4	4	5	-7	-1	3	6	-8	4	4	10
-4	8	-3	2	-2	-2	6	-4	-2	-1	3	0	1	5	0	-7	0	-6	0	5	4	-12	-6	4	-2	2	5	7	35	A320,13	36	1	0	-6	3	-2	2	0	-2	-4	-1	1	-1	-4	-5	0	8	-3	2	6	0	-3	2	-8	6	-6	6	2	7

4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	av28\ch#	1.5MHz SNR cB	av28\ch#	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
4	3	6	2	-1	0	8	-1	-9	-4	5	-2	-6	-14	-7	-2	-1	-1	1	-4	4	-1	1	9	6	-12	7	9	247	A80,11	238	-1	1	6	3	0	0	10	4	-9	-5	8	-1	-9	-7	-10	8	-5	-1	5	-6	2	2	-6	4	5	-11	2	14
																													A80,13	244	1	5	8	5	2	2	4	-4	-8	-6	6	-2	-7	-16	-6	4	-1	-2	7	-3	3	-1	0	-11	5	-8	1	11
-2	6	1	4	4	-2	4	1	-13	-7	6	1	-11	-9	1	0	-2	-2	4	-2	1	0	0	2	5	-6	3	2	245	A160,11	235	3	1	3	5	-2	-3	0	-5	-10	-7	5	2	-9	-6	-6	11	1	-2	6	-7	-3	5	-4	13	7	-12	6	18
6	7	10	4	2	2	0	-4	-10	-9	-5	-2	-7	-4	-3	-3	-4	-3	4	0	6	-2	-4	2	5	-9	5	3	250	A160,13	243	2	2	3	8	4	-1	3	-1	-13	-8	1	-6	-8	-9	-9	0	1	-3	7	-2	-1	2	-3	7	4	-8	2	15
4	1	6	5	1	0	8	-1	-10	-4	1	-2	-13	-6	-1	1	-5	1	3	-8	1	-7	-2	8	5	-12	10	7	246	A320,11	230	5	5	6	3	4	0	3	1	-12	-2	2	5	-20	-3	-6	2	0	5	9	-2	-3	3	-7	10	-5	-8	1	14
3	4	11	3	0	1	-1	-3	-6	-5	-6	-5	-8	-6	-6	2	-5	2	4	-1	4	-3	1	3	6	-9	10	8	250	A320,13	244	-1	6	6	6	1	1	7	0	-8	-11	-2	-2	-5	-7	-4	-1	0	1	2	-5	-4	-5	-7	3	3	-7	11	9

5	7	9	11	13	15	17	19	21	23	25	27	29	31	av14odd	-ones/wx cB	av14odd	5	7	9	11	13	15	17	19	21	23	25	27	29	31
5	15	4	9	-4	3	19	-3	-7	-7	-10	-10	6	-21	-326	X80,11	-325	-5	3	7	0	22	1	19	5	-10	-2	-21	-2	-7	-10
															X80,13	-323	3	-5	9	-13	16	-12	34	9	-11	-13	-14	7	0	-12
-3	11	-1	10	7	15	14	-3	-6	-11	-3	-7	-3	-19	-312	X160,11	-332	22	-11	11	-20	10	-10	18	-11	15	-13	0	-8	5	-8
6	11	0	14	-3	8	11	3	-9	-7	-3	-8	-5	-18	-308	X160,13	-309	13	-4	20	1	20	-4	32	0	-8	-10	-14	-15	-6	-24
-1	6	4	1	5	11	9	-2	2	4	3	-11	-3	-26	-290	X320,11	-301	16	-11	16	-14	10	-4	14	-7	10	-6	4	-9	2	-20
20	-2	6	-11	8	6	10	-5	4	2	-11	-1	-4	-22	-306	X320,13	-294	4	10	5	18	10	14	1	0	0	-12	3	-12	-10	-32

4	6	8	10	12	14	16	18	20	22	24	26	28	30	av14even	pip.a-ma cB	av14even	4	6	8	10	12	14	16	18	20	22	24	26	28	30
-20	15	9	7	6	6	18	-47	2	-2	4	1	1	-1	-4	M80,11	-8	-14	14	0	22	5	18	12	-67	7	0	7	-4	6	-5
															M80,13	-4	-3	5	3	5	11	8	22	-63	-6	7	4	1	7	-1
-16	13	4	23	2	14	16	-58	3	2	3	-9	10	-7	-8	M160,11	-17	-22	-30	21	-8	22	8	-3	17	-10	26	-16	12	-27	10
-18	7	4	10	10	4	10	-61	12	14	0	-1	3	7	-7	M160,13	-14	-30	19	9	21	18	16	11	-71	-4	5	7	-11	8	3
-35	16	17	25	20	20	8	-72	6	3	0	-11	6	-2	-8	M320,11	21	-55	16	12	7	10	1	16	-15	6	1	17	-13	6	-10
-36	2	9	16	4	7	17	10	-8	3	2	-11	-2	-14	-3	M320,13	-12	-35	10	20	19	5	17	16	-76	7	12	8	-8	1	4

Table 7 SP35RW & SP35WO Analog Performance Measures

This table is similar to Table 6 but for SP35. Corresponding tests of SP35 with RW and WO interfaces are presented side-by-side. SP35RW with gray labeling is to the left and SP35WO with yellow labeling is to the right. Also:

- The power units are integer centiBels, cB, for compactness.
- The individual channel entries for each test condition are shown as deviations from the average, in order to make unusually deviant channels 'stand out' on inspection.

A good example is evident in the 1 to 2 dB low SNRs of channels # 12 and 29, readily apparent in Table 7 for SP35RW and SP35WO, but, though actually of similar magnitude for WFRW and WFWO, easily overlooked in Table 6. Once noticed it can safely be concluded that these larger channel SNR deviations are primarily in the read-performance of WFRW which is 'common-mode' to all these tests.

In addition to SNR, S/WX, A-MA, slope, and curvature as in Table 6, a few other perhaps sometimes useful other analog performance and crosstalk parameters (bandedge pip amplitude, 1.5 MHz ~ mid-band SNR, bandedge 'ones' to random crosstalk ratio, and bandedge pip A-MA) are tabulated in Table 7 and here discussed.

SNR

The differences in average SNR between SP35RW and SP35WO were miniscule (.5 dB max, actually favoring SP35RW) and cannot directly explain the much poorer write-performance of SP35 with the RW-interface than with the WO-interface, evident in the 'bottom-line' error-rate comparisons in Table 2.

However, there was a hint of systematic difference between the use of RW and WO interface in average bandedge SNR as a function of write-voltage. SP35WO showed 0.6, 0.3, and 0.7 dB increases in average bandedge SNR with write-voltage increase from 11 to 13 volts at 80, 160, and 320 ips respectively. SP35RW, on the other hand, showed 0.3 dB decreases in SNR with the same write-voltage increase at 160 and 320 ips.

The simplest interpretation is that SP35WO was somewhat underdriven at 11 volts. Moderate underdrive typically has little or no direct detrimental effect on error-rate and may actually (in previous experience only with standard SP headstacks, see memo #285) minimize error-rate by reducing NLTS in worst-case channels. SP35WO does have slightly better 11 than 13 volt error-rate performance at 80 and 160 ips. As already mentioned, the 10-fold reduction in # 17s error-rate from pec = 761 to 71 in going from 13 to 11 volts at 80 ips is a good example that illustrates this effect. Because head efficiency decreases with increasing frequency the NLTS effect on #17s error-rate was reduced already at 160 ips. At 320 ips efficiency rolloff to 9 MHz eliminated NLTS and the higher 13 v drive was clearly better both for error-rate and SNR.

By the same token, SP35RW appears to be overdriven at 13 volts, and perhaps even at 11 volts. No separate mode C 80 ips optimum write-voltage determination tests were done for SP35RW, since WO and RW interfaces were thought to have identical transfer functions below the 2.25 MHz 80 ips bandedge. It was naïve however to ignore the lower frequency, hence higher Q, though out-of-band (> 15 MHz estimated) resonance of the RW interface with the ½-inductance ~ 10 uH head.

At 11 volts SP35RW had 0.5, 0.6, and 0.9 dB higher average SNR than SP35WO at 80, 160, and 320 ips respectively. Yet SP35RW had 4, 7, and 3 times poorer error-rate performance respectively than SP35WO under these conditions.

It does seem possible that lower than 11 volt write-voltage (not tried) might have brought SP35RW error-rate performance in line. However if SP35RW was overdriven at 11 volts, it would have been more heavily overdriven at 13 volts and higher error-rates would have been expected at the higher write-voltage. In fact, the opposite was observed: significantly lower error-rates at 13 than at 11 volts. I can offer no rationalization.

S/WX

Note that channel # 31 had 2-3 dB higher than average S/WX. This is because # 31 was the last active channel, the only MA 'ones' channel that received 'random' channel interference from only one side, from # 30. The small bias in average S/WX produced by # 31 has not been removed.

Average S/WX for SP35WO was 13.4, 13.6, and 10.5 dB for 80, 160, and 320 ips at 11, 11, and 13 volts respectively at which the lowest error-rates were obtained. Compared to WFWO, SP35WO had 0.5, 1.8, and 1.9 dB better S/WX.

SP35WO had its best av.pec = 34 at 160 ips, about twice the 160 ips error-rate of WFWO and equal to that of WFRW with S/WX of only 10.2 dB, 3.4 dB inferior to SP35WO.

SP35RW had its best av.pec = 108 also at 160 ips, but at 13 volts where S/WX = 11.6 dB. This was 0.5 dB poorer than 12.1 dB at 11 volts where SNR was also 0.3 dB higher, in spite of which at 11 v av.pec = 221 was twice as high as at 13 volts.

SP35WO had comparable error-rates at 80 and 320 ips with av.pec = 62 and 64 at 11 and 13 volts respectively. S/WX was about 3 dB lower for 320 than for 80 ips. NLTS seems to have limited 80 ips write-performance while write-crosstalk may have started to contribute to limiting 320 ips write-performance.

SP35RW had much higher but also mutually comparable error-rates at 80 and 320 ips with av.pec = 262 and 306 at 11 and 13 volts respectively. S/WX was 13.5 dB at 11v, 80 ips and, surprisingly, a record high 12.3 dB at 13v, 320 ips. Equally surprising, the lowest S/WX = 9.5 dB was obtained at 11v at the same 320 ips speed. This 2.8 dB reduction in S/WX with write-voltage from 13 to11 v might make sense if SP35RW were heavily underdriven at 11 v. But the opposite, somewhat overdriven operation, is indicated by the SNR data.

A-MA, slope, curvature

There were no remarkable differences or unusual channel behaviors apparent in these parameters.

Bandedge Pip Amplitude (Bepip/ran cB)

Bandedge pip amplitude was obtained by subtracting interpolated random-signal bandedge-levels from direct 2.25 MHz bandedge-power measurements. Random-signal bandedge-levels were quadratically interpolated to 2.25 MHz from the direct measurements at 1.5, 2.0, and 2.5 MHz. At these frequencies, between parity pips, the spectra are free of coherent crosstalk. The bandedge pip averages 3.6 dB in amplitude with rare deviations as large as +/- 1 dB. No consistently unusual channels or conditions were apparent.

Pip amplitude depends on resolution bandwidth, here 30 KHz, and can in principle be increased 3 dB per halving of resolution (or detection) bandwidth. Given sufficiently stable write and read speeds (stability better than 1 in 10^4), reduction of detection bandwidth from 30 KHz to 300 Hz would, for example, increase the average pip amplitude to 23.6 dB above the random-signal 'floor'.

Such dynamic range makes pip (or, better yet, synchronous parity pulse train) detection potentially useful for adjacent-channels and/or adjacent-tracks interference measurements:

- Adjacent-channel pips could be separated in frequency by encoding adjacent channels at slightly different rates. For example, simultaneous adjacent-channel Mk4, VLBA, and TBD formats could produce virtually identical indistinguishable random-signal spectra with superimposed distinguishable parity pip frequency ratios of 125:126:127.
- Adjacent tracks on the other hand are created in different passes; their parity pips could be separated in frequency even more easily by recording 3 adjacent passes at 3 slightly different speeds (without varying the formatted data rate).

'Tracking' could be monitored by measuring and comparing left-track, right-track, and on-track pip-power.

1.5 MHz SNR

Behavior of near-mid-band SNR data is here compared with that of bandedge SNR. The 1.5 MHz frequency is near peak response, which is 5 – 6 dB higher than at bandedge.

A significant >~ 0.5 dB reduction of output with an increase in write-voltage (at any in-band frequency or wavelength) is indicative of overdrive. The resulting NLTS usually causes error rates to increase rapidly with overdrive.

Note that as write-voltage is increased Metrum heads have invariably saturated tape first at the shortest wavelengths beyond bandedge, while lower frequencies (longer wavelengths) required progressively higher write-voltage for maximum response. In all known experience with Metrum heads, write-voltage just high enough to maximize bandedge output has minimized the 'inherent' error rate of a recording.

On the other hand, in more recent 1&2 Q00 tests (see memo # 285) several standard inductance and depth-of-gap SP heads behaved differently: Error rates were minimized with bandedge 1 to 3 dB underdriven. With write-voltage just high enough to maximize bandedge output, error rates were often 2 orders of magnitude higher, such that most channels failed the digital performance specification. Thus it was inferred that lower-than-bandedge frequencies on tape were overdriven by these SP heads at write-voltage just high enough to maximize bandedge output.

The symptoms observed,

- bandedge underdrive for minimum error rate, and
- midband overdrive when write-voltage maximizes bandedge response,

may not be typical of standard SP heads, since the heads tested were targets-of-opportunity with priority to diagnose problems and to re-qualify them for field use. There are indirect indications that some standard SP headstacks may not show these symptoms: In particular, one stepped SP headstack (# 46764, currently in service at Matera with good 160 ips write-performance) exhibited nearly acceptable error rates at 320 ips write-speed (see memo # 273 by D. Smythe).

For SP35WO, the half-inductance and half depth-of-gap experimentally improved SP prototype with the 1000-ohm WO interface, neither the bandedge underdrive nor the midband overdrive symptom was evident in the 28-channel averages of analog performance measures:

- 13 minus 11 volt average SNR at 1.5 MHz was 0.6, 0.8, and 1.4 dB at 80, 160, and 320 ips respectively; that is, mid-band was apparently not overdriven at 13 volts.
- The 13 volt average SNR at 1.5 MHz was 24.4 dB independent of write-speed within -0.1 dB; the 13 volt average SNR at 2.2 MHz was 19.0 dB also independent of write-speed within +/- 0.1 dB.
- 13 minus 11 volt average SNR at 2.2 MHz was 0.6, 0.3, and 0.7 dB at 80, 160, and 320 ips; that is, underdrive at 13 volts was insignificant and small < 1 dB at 11 volts.

At 320 ips, average error rate was clearly lower by a factor of 2 at 13 than at 11 volts.
At 80 ips, excluding 'outlier' # 17, the corrected av.pec = 42 at 13 volts, lower than av.pec = 62 at 11 volts.
At 160 ips, the lowest pec = 34 was obtained at 11 volts, though this may not have been significantly better than pec = 50 at 13 volts.

Outlier channel # 17 however does show mid-band overdrive at 13 volts 80 ips, in conjunction with anomalously high error rate (pec = 761):

- Its 13 minus 11 volt SNR at 1.5 MHz was –0.3 dB, indicating midband overdrive.
- At 2.2 MHz its 11 to 13 volt SNR increment was exceptionally large at + 2.2 dB compared to average of 0.6 dB. This may be due to 2nd harmonic response of overdriven midband.
- At 11 volts # 17's pec = 71 was an order of magnitude smaller and close to av.pec = 62, that is, much better with apparent bandedge underdrive > 2.2 dB.

At 13 volts 80 ips channel # 27 also exhibited mid-band overdrive along with the second highest pec = 155:

- Its 1.5 and 2.2 MHz 11 to 13 volt SNR increments were –0.9 and +1.5 dB respectively.
- However, at 11 volts, # 27's pec = 140, unlike # 17's, was not much better than at 13 volts.

At 80 ips, there were no other channels with mid-band overdrive at 13 volts.
At 160 ips, only one channel, # 19, was slightly overdriven at 13 volts with 1.5 MHz output 0.3 dB less than at 11 volts. Though pec = 55 was good at 13 volts, it was 3.5 times better at 11 volts with pec = 16.
At 320 ips, no channels were overdriven in mid-band at 13 with respect to 11 volts.

Near bandedge at 2.2 MHz, the only instance of significant overdrive at 13 with respect to 11 volts was for channel # 30 at 320 ips write-speed: 2.2 MHz output was 1.2 dB less at 13 than at 11 volts.

- This bandedge overdrive should have caused an abnormally high error rate.
- Instead, # 30 at 13 volts 320 ips was also the only instance of pec = 0.
- I can think of no explanation except possibly a measurement error.

-Ones/WX and Pip.A-MA in cB (centiBels)

These measures are the direct A minus MA difference at the 2.25 MHz bandedge for odd and even channels respectively:

- The first are 'random' mode A minus 'ones' mode MA bandedge levels, large (negative) values, since 'ones' recordings are essentially pure coherent bandedge signal. The 'random' mode A bandedge signals are dominated by the parity pip whose amplitude may be affected by in-phase coherent interference in the case of channel # 17 or one-sided non-canceling interference in the case of # 31.

- The second is the A minus MA difference in bandedge pip amplitude for the even channels -- which recorded random signal in both mode A and MA. An in-phase coherent interference effect was observed in channel # 18. The effect of one-sided interference was evident in channel # 4.

Attention is called to:

1. Average amplitude of Ones/WX decreased with increase of write-voltage from 11 to 13 volts. The 11 volt 32.5, 33.5, and 30.1 dB values at 80, 160, and 320 ips decreased by 0.2, 2.3, and 0.7 dB respectively at 13 volts. If the average Ones response increased with write-voltage by 0.6, 0.3, and 0.7 dB as in mode A (item 1 in Table 7 first discussed), the average 11-to-13 volt increase in coherent bandedge write-crosstalk in mode A was 0.8, 2.6, and 1.4 dB at 80, 160, 320 ips respectively.

2. Channel # 17, both at 80 and 160 ips write-speed, exhibited 3.5 and 3.2 dB more than average WX (coherent bandedge mode A) at 11 and 13 volts respectively. The high WX level is attributed to in-phase coherent two-sided parity-pulse-train interference from adjacent channels # 16 and 18. The two channels # 16 & 18 adjacent to # 17 are mutually in-phase due to an otherwise harmless oversight in system configuration: The Mk 4 formatter interface design ignored the intentional polarity inversion of complementary channel signals in mid-connector (that is, mid-headstack between # 16 & 18 and # 17 & 19 for even and odd channel connectors respectively, in VLBA head-driver interfaces).

3. The remaining odd and even next-to-adjacent channels are wired 180 degrees out-of-phase by virtue of the head-interface layout: Coherent interference from these was expected to cancel to first order. Nevertheless, the remaining channels with 2-sided interference show variations of up to about +/- 2 dB about average Ones/WX.

4. Channel # 31 had only one-sided interference from # 30. The fact that it had the highest Ones/WX ratio by far at 320 ips, 3.2 dB above average at 13 volts, was rationalized as follows:
   - The other MA ones channels, it was inferred, suffered a reduction in written amplitude due to two-sided write-interference from adjacent random MA channels. The inference was necessary because I did not have the foresight to make mode C ones recordings free of adjacent channel write-crosstalk for direct comparison.
   - Two independent random channels, both adjacent to a third sandwiched channel, are mutually in-phase 50 % of the time. This double-amplitude write-current interference is coupled to the sandwiched channel, 25% of the time adding to, and 25 % of the time subtracting from, its ‘intended’ write-current.
   - Sufficiently large coupling results in overdrive when adding, and underdrive when subtracting. As overdrive increases, to first order, a significant increase in error-rate in mode A can be expected even before the recorded bandedge signal amplitude is significantly reduced, by more than ~ ½ dB. On the other hand, the underdrive which occurs with the same 25% duty-cycle as overdrive in the two-sided write-crosstalk affected channel, can be expected to first order, to significantly decrease written-signal amplitude, by several dB, before error rate begins to increase noticeably.

- The MA ones channel # 31 did not, to first order, see the last effect, a significant decrease in average written-signal amplitude due to sufficiently high amplitude 25% duty-cycle underdrive. This was because maximum adding and subtracting write-current interference from random # 30 was only half that to which the other MA ones channels were subjected with two-sided interference. And because the written-response is non-linear with respect to total write-current, that is, half the maximum write-current perturbation produces far less than half the reduction in written-response.
- The ~ 3 dB bandedge pip amplitude of channel # 31 in mode A was quite normal, as were the bandedge pip amplitudes of the remaining channels in mode A. If this had not been the case the inference of the first bullet would have been more questionable.

5. Random channel # 4 in mode MA had 1-sided interference from ones channel # 5: As a result, at 320 ips 13 volts, #4's bandedge parity pip was enhanced by ~ 5 dB, that is, increased in size from normal ~ 3 to ~ 8 dB. This level was ~ 15 dB below the ones level of channel # 5.

6. Random channel # 18 in mode MA had in-phase coherent 2-sided interference from ones channels # 17 & # 19: As a result, at 320 ips 13 volts, # 18's bandedge parity pip was enhanced by ~ 9 dB, that is, increased in size from ~ 3 to ~ 12 dB. # 18's bandedge level was ~ 12 dB below the ones level of channels # 17 & # 19.

7. The remaining even-numbered channels in mode MA had opposed-phase, to first order canceling, coherent 2-sided interference from pairs of odd-numbered adjacent channels, and thus the least write-crosstalk: These remaining random channels had normal ~ 3 dB bandedge parity pips, with level ~ 20 dB below the typical ones levels of the adjacent channels. Though pip.a-ma varies by as much as +/- 2 dB for these channels, this variation is small compared to the effects of 1-sided or in-phase 2-sided coherent ones interference in # 4 and # 18 respectively.

SP35RW vs. SP35WO: Influence of RW vs. WO Interface on Analog Measures of Write Performance

Compared here finally are the effects on analog measures of write performance of the two interfaces, 'RW' and 'WO', with both of which SP35's write performance was extensively tested.

I found hints in the following details of this comparison as to the cause(s) of the rather poorer digital write-performance observed with the RW than with the WO interface.

I concluded that the write-performance of the RW interface would probably be improved with a lower input-capacitance 1st-stage emitter-follower such as has been qualified for new high-speed read-only interfaces for Mk4 processor drives.

For SP35RW average bandedge SNR was slightly ~ 0.3 dB lower at 13 than at 11 volts, where it was 19.2 dB. This indicates slight overdrive at 13 volts. However, error rates were lower at 13 than at 11 volts, which is contrary to expectation for overdrive at the higher write-voltage.

By comparison, for SP35WO average bandedge SNR was 0.3 to 0.6 dB higher at 13 than at 11 volts, and equaled 19.0 +/- 0.1 dB at 13 volts for all 3 write-speeds.

I inferred that SP35RW, due to the capacitive loading of the EF transistor in the RW interface, had a much lower resonance frequency and higher Q than WO, hence probably more than 20 % write-current overshoot. This would explain the maximized written bandedge response at 11 volts and slight overdrive at 13 volts for RW, as well as the not-quite-maximized written response at 13 volts for WO.

I note that the write-process doesn't to first order 'filter out' write-current overshoot.

Recordings look roughly as if write-current had maintained its peak value for about one bit-time (since the 'write-bubble' within which the magnetic write field exceeds tape coercivity is about one gap-length ~ bit-cell long) even if the actual write-current overshoot persists for only a small fraction of one bit-time.

Thus 'ones' (write-current or flux reversals) are written ~ with DC + overshoot current, while any following 'zeros' (during which write-current is in principle held constant) are actually written ~ with just the DC current. If there is significant current overshoot, ones will be overdriven and/or zeros underdriven. Just how and how much error rates will thereby degraded is difficult to predict. The present heuristic argument is too qualitative; I have not been able to find or develop a quantitative model.

At 320 ips write-speed, average bandedge S/WX for SP35RW was 9.5 and 12.3 dB at 11 and 13 volts, 1.3 dB worse and 1.8 dB better respectively than the nearly equal 10.8 and 10.5 dB values for SP35WO.

Yet av.pec = 64 was lowest for SP35WO at 13 volts, not for SP35RW with 5 times poorer av.pec = 306 in spite of its best 12.3 dB 320 ips S/WX figure of merit.

Furthermore, WFRW, with the poorest 6.9 dB 320 ips average S/WX, nevertheless had reasonably good av.pec = 102. (Even its worst 5.3 dB S/WX channel # 11 had good pec = 93, while worst pec = 274 channel # 15 had S/WX = 6.7 dB.)

Thus it is clear only that the halved inductance of the 35-turn SP head resulted in better S/WX performance than was obtained with either of the two standard-inductance 48-turn Metrum headstacks with which it was compared. This was qualitatively as expected.

With the RW interface (not with WO) however, the 320 ips high-speed S/WX of SP35 developed a sharp dependence on write voltage, that is, S/WX improved ~ 3 dB from 11 to 13 volts. I remain unable here to rationalize this strong observed dependence of S/X on write-voltage.

The small corresponding drop from av.pec = 443 to 306 in spite of high 12.3 dB S/WX, as well as the not much better av.pec = 262 for SP35RW at 80 ips write-speed, with even better S/WX = 13.5 dB, indicates to me that write-crosstalk was not the dominant cause of the higher error rates characteristic of SP35 recordings which used the RW interface.

The average spectral slope was slightly 0.3 and 0.5 dB/(0.5 MHz) greater for RW than for WO at 11 and 13 volts respectively, at both 160 and 320 ips write-speed.

Consistent with this is the fact that midband 1.5 MHz SNR at 11 volts was 1.0 and 1.6 dB higher for RW than for WO at 160 and 320 ips respectively. At 13 volts RW-WO was smaller, 0.7 and 0.6 dB respectively.

Thus midband was closer to saturation with RW than with WO at 13 volts, while bandedge was slightly overdriven with RW and very slightly underdriven with WO at the same write-voltage.

The several differences noted here between SP35 spectra written with RW versus with WO were small, but all seem consistent with substantial resonant write-current overshoot for RW, due to ~ 8 pF max. capacitive loading of the 3906 preamp emitter-follower.

Somewhat vertically asymmetric eye patterns were also noticed in playback of SP35RW recordings. This symptom, indicating a form of written nonlinear intersymbol interference, is thought to be due to the strongly asymmetric dependence of base input capacitance on the sign and magnitude of the applied write-voltage.

These symptoms should be virtually eliminated by substituting a low < 2 pF input capacitance transistor for the 3906. I would then expect error rate performance comparable to that observed with WO.

Non-linear intersymbol interference, due to overdrive, overshoot, and/or asymmetric write-current transitions, was unfortunately here only indirectly observed with a spectrum analyzer.

More sensitive and direct means of measuring phase response and waveform distortions in the time domain were not available, but should be found if write-channel integrity tests are to be further developed.