TELEMETRY LINK RELIABILITY IMPROVEMENT VIA “NO-HIT” DIVERSITY BRANCH SELECTION

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ABSTRACT

Multipath propagation consisting largely of specular reflection components is known to be the major channel impairment in many aeronautical mobile telemetry (AMT) applications. Adaptive equalizers are not effective against flat fading commonly created by strong power delay profile components representing small fractions of the transmitted symbol period. Avoidance and diversity techniques are the only practical means of combating this problem. A new post-detection, no-hit diversity branch selector is described in this paper. Laboratory and limited flight test data comparing non-diversity, selection diversity and intermediate frequency (IF) combining techniques are presented.

KEYWORDS

Diversity, aeronautical telemetry, optimal ratio combining, selection combining

INTRODUCTION

In 2002 the United States Department of Defense (DoD) Advanced Range Telemetry (ARTM) project commissioned the development of a stand-alone diversity branch selector to supplement demodulators developed for the constant envelope (CE) offset quadrature phase shift keying (OQPSK) modulations recommended in reference [1]. At that time, auxiliary data captured during a series of ARTM channel sounding experiments confirmed that signal fading remains highly correlated in dual left-hand and right-hand circularly polarized (LHCP and RHCP) receiving antenna configurations commonly used at open-air test ranges. Thus, pre-detection (pre-D) combining of these signals is not effective in combating the severe bit detection error clusters and detector synchronization failures seen in AMT links when directional receiving antennas are used at low pointing angles [2]. The same series of experiments and additional flight experiments involving side-by-side performance comparisons of various modulation techniques clearly showed that spatial and frequency diversity reception offer substantial opportunities to *avoid* short-term multipath propagation effects.

The prototype two-channel diversity branch selector (DBS) shown in figure 1, designed and built by RF Networks Inc. of Phoenix, Arizona, was delivered to the ARTM project in February of 2004. This paper summarizes its pertinent specifications and discusses DBS performance data acquired to date.

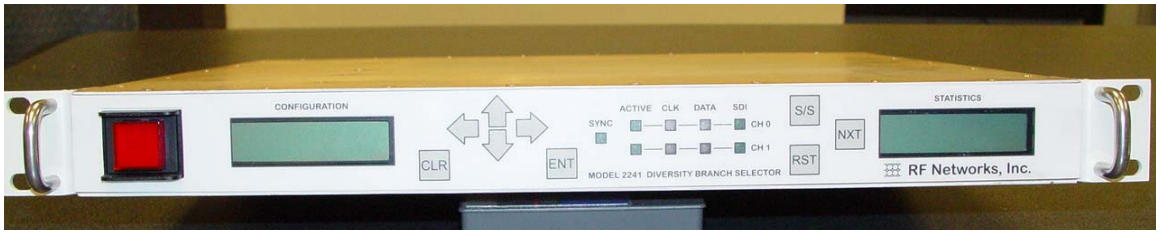

Figure 1 – Prototype Diversity Branch Selector

ARGUMENTS FOR POST-DETECTION BRANCH SELECTION

In his classic paper on the subject of diversity signal processing, Brennan clearly demonstrated that optimal ratio combining (ORC) outperforms channel selection and equal-gain combining in most circumstances [3]. However, the benefits of ORC are not realized unless four conditions are satisfied [3]. In the case of pre-D combining, one condition is particularly confining. The signals to be summed must be phase aligned, having essentially the same zero crossings. Inter-channel phase adjustment of angle modulated signals in receivers or intermediate frequency (IF) combiners is not trivial even when inter-channel propagation delays are small fractions of the symbol period. Many AMT data streams operate at bit rates greater than 5 megabits/second (Mb/s) today and the trend is toward higher rates as suitable instrumentation and techniques become available to support them. At some point, inter-channel phase alignment is likely to become intractable.

Spatial diversity presents serious challenges to signal combining instrumentation. Many DoD receiving sites have multiple antennas with sufficient vertical separation to create useful signal diversity but they are normally separated by 10s to 100s of feet horizontally. In these situations, inter-channel delay consists of static and dynamic components that can be larger than a symbol interval. Dynamic delay and phase adjustment of RF or IF signals for combining is a daunting challenge, one considered impractical at this time. On the other hand, post-detection time alignment of digital bit streams having arbitrarily large delay relationships is comparatively easier and quite practical with modern digital circuit technology.

Traditional diversity performance analysis focuses on metrics like signal to noise ratio (SNR) and average bit error probability (BEP). The BEP can be a highly misleading figure of merit in short and intermediate range AMT applications (up to about 350 km). Most AMT systems are designed with conservative power margins to provide BEPs on the order of 1×10^{-5} at maximum operating range with fade margins ranging from 3 to as much as 15 dB. The result is a telemetry link that operates at high SNR most of the time and exhibits on/off behavior, i.e., long periods of error free transmission interrupted by short-term catastrophic outage intervals induced by multipath propagation [2]. In these situations, marginal gain enhancement is not important because increased SNR will not overcome the cause of the short-term link failures. The goal of diversity processing is reduction of extent and severity of short-term link failures with *affordable* methods.

DBS GOALS AND REQUIREMENTS

Consideration of these arguments led to the decision that a post-detection selector could provide the following benefits to AMT systems:

- Easy, non-invasive addition of diversity processing to existing facilities
- Compatibility with a wide range of diversity techniques, e.g., frequency, spatial, polarization, arrival angle
- Performance largely independent of SNR and fading distributions
- Automatic adaptation to a wide range of bit rates
- Automatic adaptation to a wide range of static and dynamic inter-branch delay

Figure 2 outlines the system configuration assumed for DBS operation. Two independent receivers provide 20 or 70 MHz IF signals to a pair of CE OQPSK demodulators. The receivers provide appropriate automatic level control and coarse band limiting filter functions. The demodulators create post-detection serial non-return to zero (NRZL) bit streams and coherent bit strobe clocks, one pair per diversity branch. Each demodulator provides channel signal quality intelligence to the DBS with the “signal degradation indicator” (SDI) technique described in reference [5]. The SDI is a modified form of shifted threshold pseudo-error detector. Short serial digital messages provide periodic updates on signal quality and demodulator synchronization status at rates ranging from 400 to 480 messages/second.

Figure 3 is a simplified diagram of DBS operation. High-speed correlators and adaptive temporary storage devices continuously monitor and compensate for inter-channel bit timing offset. The goal is to

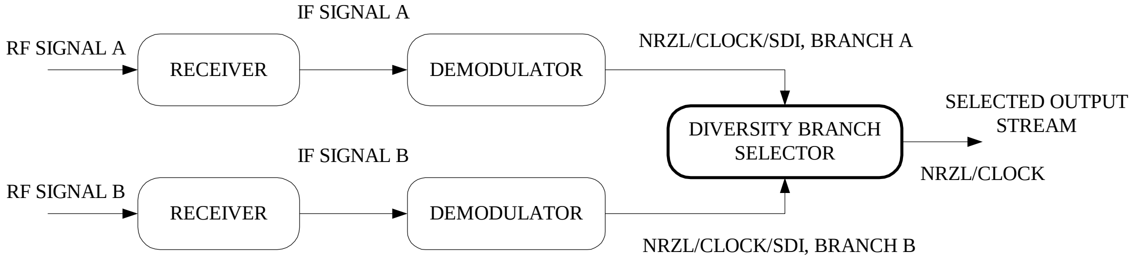

Figure 2 - System Configuration

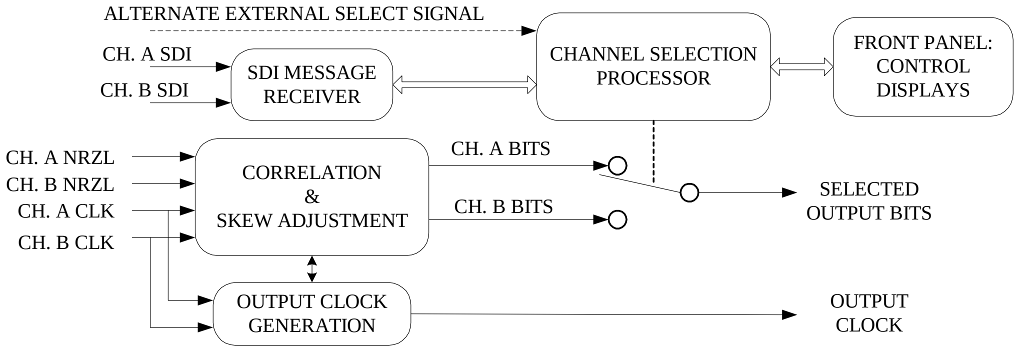

Figure 3 - Basic DBS Functions

create pointers into both streams that are always pointing to the same bit of the original transmission. The output clock generator synthesizes a continuous bit strobe from the input bit strobes and correlation operations. It is designed to minimize occurrence of bit slips or ‘hits’ in the output bit stream caused by repeated switching from one data source to the other, hence the term ‘no-hit switch’. The channel selection processor receives SDI messages from both demodulators and decides which channel will be selected for output over the next SDI message update cycle. Thus, source selection is applied to small blocks of bits, not individual bits. The DBS output consists of a NRZL stream of “selected” bits and a continuous bit strobe. Significant performance requirements addressed in the design include:

- Input bit rate: automatic adaptation to rates in range of 0.5 to 20 Mb/s, minimum
- Inter-channel time offset compensation: fully automatic, ±10 microsecond range
- Inter-channel correlation reliability and speed: guaranteed time skew identification and compensation within 1,000 bit periods at BEPs of 0.05 and lower, each channel
- Output bit rate: no systematic change to input rate
- Automatic branch selection options:
  - based on SDI signal intelligence at intervals consistent with SDI message rates
  - user supplied channel selection control (discrete logic signal) in lieu of SDI
- Manual override: forced selection of either branch via front panel control
- Channel condition statistics: extraction and display of individual channel condition statistics derived from SDI messages over user-defined measurement periods

LABORATORY TESTS

The manufacturer provided adequate evidence of specification compliance in the areas of basic functions and inter-channel correlation performance. Government lab tests concentrate on performance assessment beyond the capability of equipment available to the manufacturer. Specifically, a channel simulator (Telecom Analysis Systems model TAS 4500) is used to emulate dynamic channel distortion conditions somewhat similar to field conditions. Situations similar to spatial diversity reception are established with the equipment shown in figure 4. The channel simulator provides adjustable static inter-channel delay as well as independent repetitive sweeps of 2-ray and 3-ray multipath notches across the signal passband over a wide range of excess delay and inter-ray power ratio settings. Notch sweep rate is controlled by adding a small Doppler shift to each path (ray) relative to the line-of-sight (LOS) path.

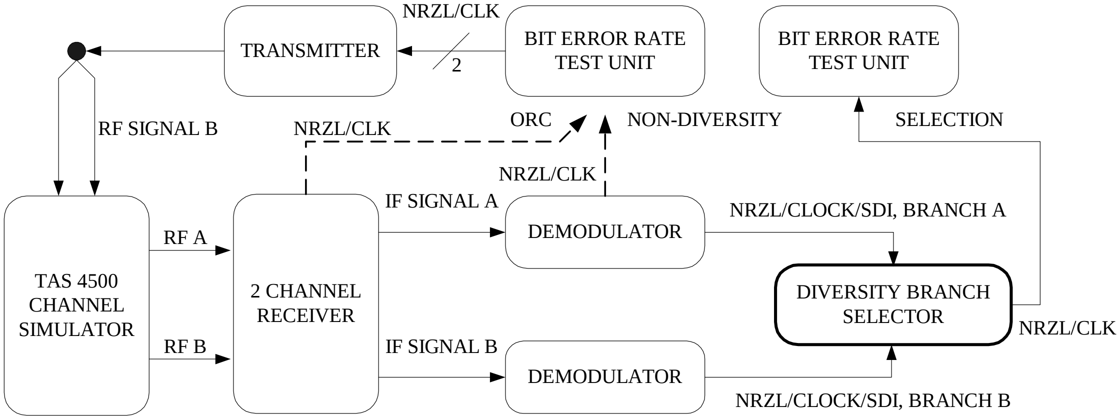

Figure 4 - Lab Test Configuration

Diversity is created by offsetting the Doppler shift in one channel relative to the other. Additive receiver front-end noise is used to control SNR. The receiver was an L-3 Communications model RCB-2000, a dual channel receiver with integral IF ORC combiner and internal CE OQPSK demodulator. The demodulators were RF Networks Inc. model 2120. While this setup does recreate multipath notches consistent with measured field conditions, inter-channel time correlation of notch sweeps cannot be controlled directly. Consequently, notch sweep intervals are short and the timing of notch sweeps in the channels is not consistent with real situations. Short sweep intervals and attendant short measurements periods force us to use bit error measurements rather than the link availability statistics used in field work. Further, short fade intervals coupled with deterministic fading correlation yield artificially high bit error statistics. Nonetheless, these tests are sufficient to determine whether the DBS is ready for flight trials.

Static delay insertion with and without multipath distortion confirmed that the DBS does correctly identify and compensate for channel time skew over the required range. To date, distortion tests have been limited to 2-ray multipath scenarios with excess delays of 40 and 100 nanoseconds (nsec). Relative path loss in the 2nd ray (relative to LOS ray, each channel) has been limited to values of 0.9 dB at 40 nsec delays and 6 dB with 100 nsec delays. These values are consistent with severe fade conditions seen in previous field tests [4].

Table 1 (see appendix for all data tables and figures 5 through 8) presents 5 representative lab data sets. Each test was 5 minutes in duration. Notch sweep rates were 2/second on channel A and 1.8/second on channel B and the SNR was 20 dB (each channel). The first row represents repetitive flat fades due to short excess delay. Both demodulators exhibited brief synchronization failure during each sweep. Both diversity processing methods produced significant improvement over the non-diversity system. Next, at 7.5 Mb/s, the fading is frequency selective and there was significantly less time dispersion of fade severity between channels than the previous case due to increased signal bandwidth. Improvement factors for the DBS and ORC are 5:1 and 5/3:1 respectively. At 15 Mb/s and 40 nsec delay, the non-diversity system is virtually useless but both diversity systems remained in service and the ORC equipment outperformed selection diversity (an expected outcome).

FIELD TESTS

The first flight test opportunity was May 5, 2004 at Edwards Air Force Base, California. Three sorties were flown over a two-week period in three of the flight corridors used for channel sounding experiments. A pair of 1.2 meter receiving antennas was used for spatial diversity reception. One was placed atop an abandoned radar building and the second was mounted on the ARTM mobile receiving station. No attempt was made at ‘optimum’ antenna separation. Vertical antenna separation was approximately 20 feet. Horizontal offset was approximately 80 feet. Both antennas had unobstructed views to the horizon in the required directions. The receiving equipment was similar to the lab configuration. However, 2 M/A-Com model 5550i receivers were substituted for the RCB2000 and no ORC equipment was available. The signal source consisted of a 10 Watt SOQPSK-TG transmitter connected to a single blade style omni directional antenna mounted on the belly of a U.S. Air Force C-12 twin turboprop airplane. Continuous repetitions of a 2047 bit pseudo-random binary sequence were transmitted at 5 Mb/s. Carrier frequencies ranged from 1450 to 1500 MHz. Bit error and ITU-T Recommendation G.821 [6] (G.821) link availability statistics were captured with Fireberd 6000 bit error test sets (Acterna Corp.) at 5 second intervals. The SDI messages from both demodulators were recorded continuously to disk files. Antenna pointing angles were kept low by design (less than 5 degrees above horizon) in order to subject the systems to as much multipath as is available in these corridors. Pressure altitude varied from 2,300 feet to 10,000 feet and indicated airspeed ranged from 200 to 250 knots. During test runs, the LOS distance between the aircraft and the receiving site ranged from 20 to 70 nautical miles. With the exception of one intentional climb (to increase rate of multipath fade production), all measurements were taken with the aircraft flying straight and level.

Summary data are presented in Table 2. From left to right, the column labels are: flight corridor identification (corridor ID/nominal direction of flight/flight number), measurement period (T_m) in seconds, G.821 “error free seconds” provided by both systems (EFS_{n-d} and EFS_D), “failed seconds”[1] experienced in both systems (FS_{n-d} and FS_D), the number of times the DBS switched between channels (DBS cycles), and link availability of both systems (LA_{n-d} and LA_D). Simplified LA values are used here:

$$LA_x = 100\left(1 - \frac{FS_x}{T_m}\right) \quad (\%) \qquad (1)$$

Improvement factors I_x for EFS and FS are listed in the last two columns. These are simple percentage improvement numbers computed with the non-diversity system used the reference, i.e., positive values indicate better DBS system performance.

The LA and FS improvement numbers indicate improvement in the DBS channel in all but three test runs. However, before one can assess the significance of these results, it remains to determine the extent to which useful time domain diversity existed. A coarse estimate of *potential* diversity improvement is obtained from SDI data. The SDI records of both channels are examined sequentially in 1-second blocks. If all SDI message pairs within a block show no significant channel degradation, the block is labeled error free, with no potential for performance improvement. If severe SDI activity ($BEP > 1x10^{-4}$ or demodulator synchronization failure) is seen in one channel or both, but severe activity messages are always exclusive to one channel or the other, then the interval is counted as having *potential* for conversion to an error free interval by DBS action. Otherwise, if the majority of severe SDI indications overlap, the interval is counted as a failed second with no improvement potential.

Figure 5 compares potential DBS FS improvement derived from SDI data to FS improvement *realized* in the test runs of flight 71. In three runs the DBS did capitalize on most of the potential improvement. However, the –16% value of test point “1/E/71” is clearly not consistent with a prediction for as much as 31% improvement. Symptoms leading to this discrepancy can be discerned by examination of figures 6 through 8. Figure 6 is the progression of accumulated FS_{n-d}, FS_D, and I_{FS} for this run. Both channels experienced nearly continuous severe error conditions in the first 50 seconds of the run. In this run segment the DBS channel generated bit errors at nearly twice the rate of the reference channel and accumulated a very large I_{FS} deficit that was never offset by improvements realized later in the run. I_{FS} also jumped abruptly downward approximately 240 seconds into the run.

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[1] In this application we have defined “failed” seconds as the sum of G.821 “severe error seconds” and G.821 “unavailable seconds”.

From previous experiments it is known that the west end (beginning) of this run produces severe multipath distortion. The aircraft is relatively close (approximately 20 nautical miles) and at low altitude. The receiving antennas see signals reflected from mountains behind the aircraft and possibly from manmade objects in a nearby town that lies between the receiving site and the aircraft. The severity of fading is increased by the fact that small receiving antennas were used. Larger antenna apertures (by at least a factor of 2) are the norm in these applications and our test therefore represents an extreme set of conditions. Figure 7 is the time history of raw SDI data from this run. Channel B data are inverted to assist visual comparison. The scale of this plot is not linear. Values in the range of 0 to 100 represent low to moderate distortion. Severity increases rapidly above 100. SDI values of 400 are the point of pending demodulator synchronization failure. Synchronization status is superimposed near the top of the plot. The upper logic trace is channel A. Logic low values represent synchronization failure. Little detail can be gleaned from this compressed time scale but the plot does emphasize the fact that the beginning segment of this run produces severe channel degradation. Figure 8 zooms the time axis of figure 7 to reveal detail. Rapid, repetitive severe channel degradation is apparent and we see that channel B experienced numerous and sustained synchronization failures. Apparently, these conditions cause a problem for the DBS channel. At the end of each run the number of data pattern losses and pattern slips logged by the bit error test sets was recorded. The DBS channel produced a significant number of pattern slips (bit slips). Note also, that the number of DBS cycles seems disproportionately large in runs that produced poor improvement factors. It appears then, that the DBS may not be acting as a no-hit switch under these conditions. Possible causes of this behavior are under investigation.

The balance of this test run shows significant spatial diversity potential and good realization of that potential. Similar good performance was found in all of the other cases as well. Even if the source of the anomalous behavior were not identified and cured, less stressing channel situations could profit from use of this equipment in its present form.

CONCLUSION

Preliminary DBS field tests are encouraging. Under a fairly wide range of serious channel degradation conditions it can profitably exploit available diversity. One problem area has been described but its cause is not yet understood. These tests also show that the SDI signals are reliable channel selection intelligence sources under a wide range of channel conditions. Additional work is scheduled for the summer of 2004 that will include frequency diversity tests, inclusion of ORC equipment for comparison purposes, and possible refinement of the SDI-based channel selection algorithm.

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[6] “Error performance of an international digital connection operating at a bit rate below the primary rate and forming part of an integrated services digital network”, ITU-T Recommendation G.821, International Telecommunication Union, August, 1996.

APPENDIX

Table 1 – Laboratory Fade Test Examples

Bit Rate (Mb/s)	Static Inter-channel delay (nsec)	Multipath Excess Delay (nsec)	BEP (non-diversity)	BEP (selection)	BEP (optimal ratio)
1	0	40	$2x10^{-4}$	$8x10^{-6}$	$9x10^{-6}$
7.5	0	40	$5x10^{-2}$	$1x10^{-2}$	$3x10^{-3}$
15	0	40	0.2	$5x10^{-2}$	$2x10^{-2}$
15	0	100	not measured	$4x10^{-2}$	$3x10^{-2}$
15	70	100	0.2	$4x10^{-2}$	failed

Table 2 – Flight Test Results

Test ID	T_m (sec)	EFS_{n-d} (sec)	EFS_D (sec)	FS_{n-d} (sec)	FS_D (sec)	DBS cycles	LA_{n-d} (%)	LA_D (%)	I_{LA} (%)	I_{FS} (%)
1/W/69	1506	1172	1184	215	208	6751	85.7	86.2	0.5	3.3
1/W/70	1291	1189	1240	19	5	946	98.5	99.6	1.1	73.7
1/W/71	1046	990	1008	24	13	1118	97.7	98.8	1.1	45.8
1/E/69	1506	1172	1184	229	149	1927	84.8	90.1	5.3	34.9
1/E/70	1346	1106	1130	116	89	2570	91.4	93.4	2.0	23.3
1/E/71	1037	900	923	61	71	2991	94.1	93.2	-1.0	-16.4
2/W/69	1022	793	892	45	25	575	95.6	97.6	2.0	44.4
2/W/70	1376	1252	1279	31	33	1282	97.7	97.6	-0.1	-6.5
2/W/71	882	779	791	2	1	86	99.8	99.9	0.1	50.0
2/E/69	687	529	572	37	10	172	94.6	98.5	3.9	73.0
2/E/70	821	694	711	43	32	891	94.8	96.1	1.3	25.6
2/E/71	917	784	841	36	3	137	96.1	99.7	3.6	91.7
3/SE/70	626	511	534	71	76	2940	88.7	87.9	-0.8	-7.0

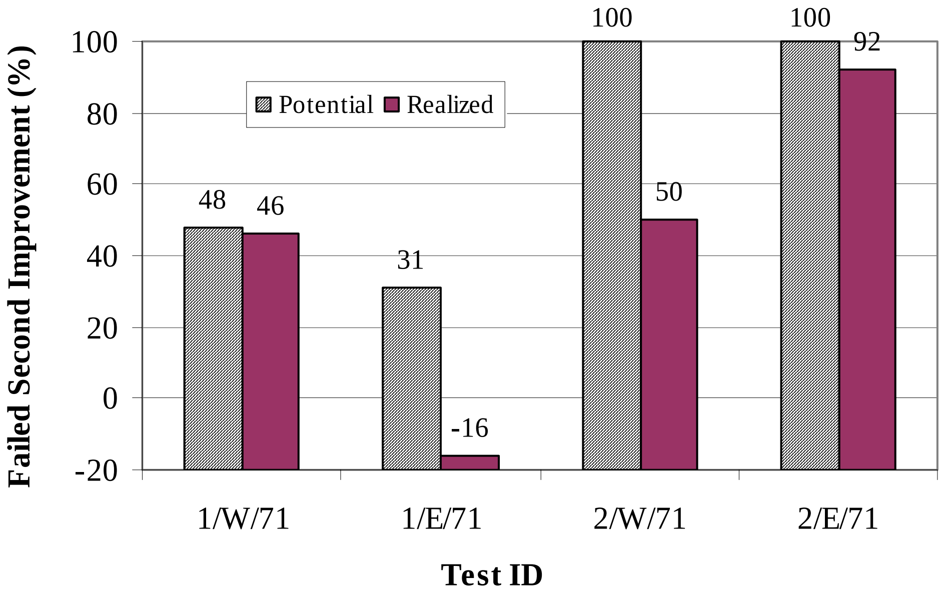

Figure 5 – Failed Seconds Improvement

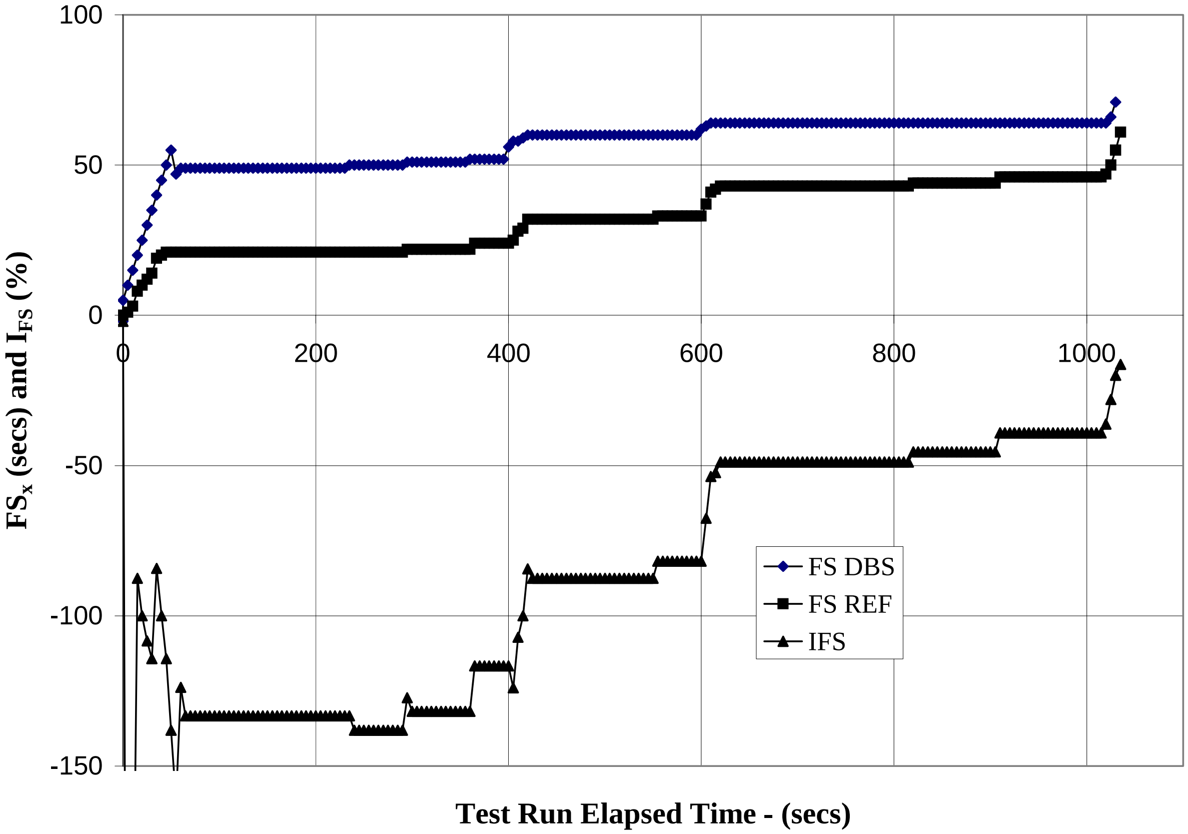

Figure 6 – Time History of Failed Seconds and Failed Second Improvement Factor

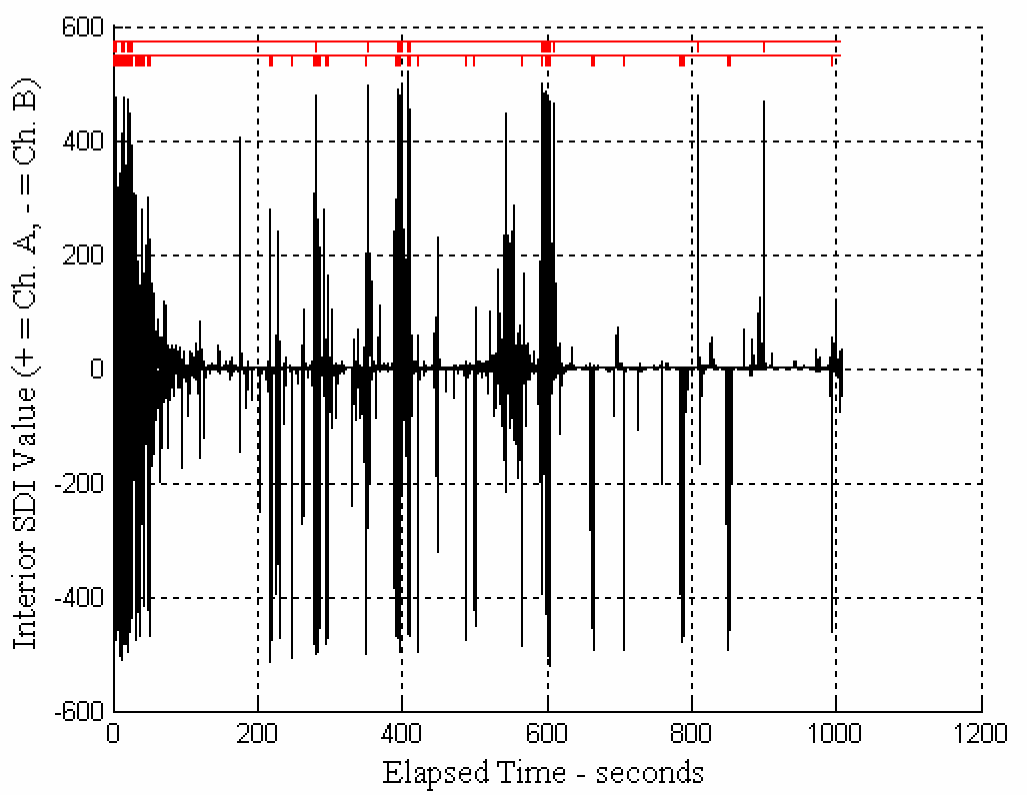

Figure 7 – Time History of SDI Data, Flight 71

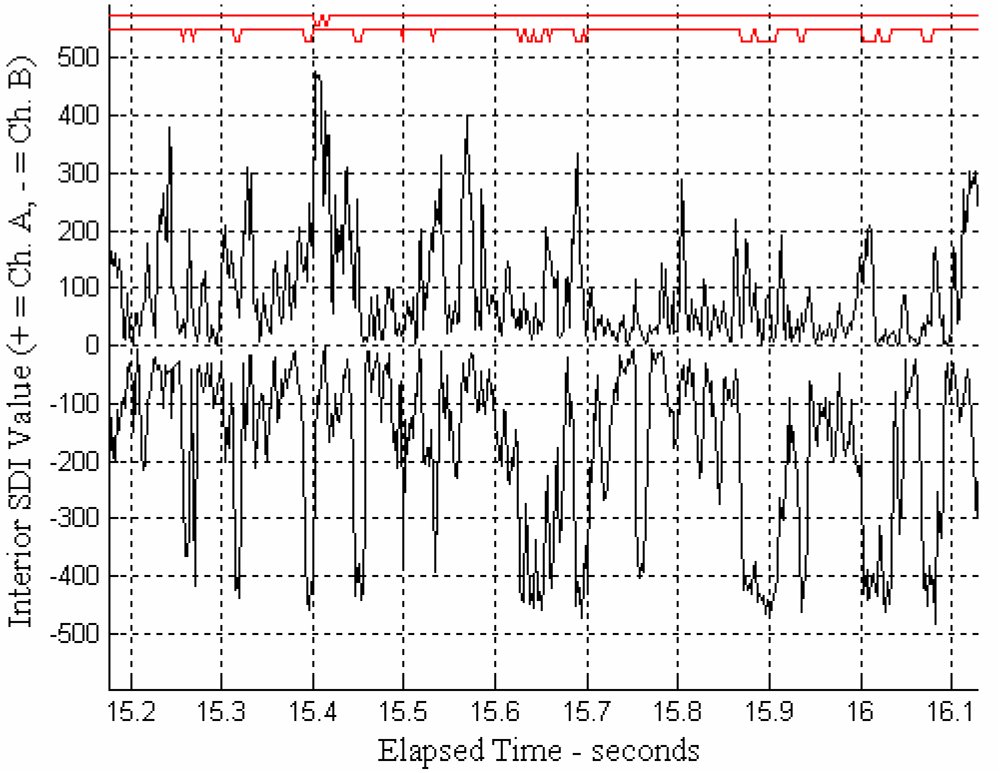

Figure 8 – Time Axis Zoom of Figure 7