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Report on Earth Observation Application

# Landsat Data Continuity Mission (LDCM) - Optimizing X-band Usage

**Summary:**
The NASA version of the low-density parity check (LDPC) 7/8-rate code, shortened to the dimensions of (8160, 7136), has been implemented as the forward error correction (FEC) schema for the Landsat Data Continuity Mission (LDCM). This is the first flight application of this code. In order to place a 440 Msps link within the 375 MHz wide X band we found it necessary to heavily bandpass filter the satellite transmitter output . Despite the significant amplitude and phase distortions that accompanied the spectral truncation, the mission required BER is maintained at < $10^{-12}$ with less than 2 dB of implementation loss. We utilized a band-pass filter designed ostensibly to replicate the link distortions to demonstrate link design viability. The same filter was then used to optimize the adaptive equalizer in the receiver employed at the terminus of the downlink. The excellent results we obtained could be directly attributed to the implementation of the LDPC code and the amplitude and phase compensation provided in the receiver. Similar results were obtained with receivers from several vendors.

**Background:**
New near-earth missions are continually pushing for higher data throughput. Sensors planned for installation aboard demand ever increasing associated data rates. Ground station infrastructures have in turn seen the benefit of improved efficiencies in the handling and distribution of mission data such that their capacities have improved dramatically as well. In contrast, the X-band spectrum allocated to near-earth missions (8025 to 8400 MHz) is constrained. In keeping with the output capabilities of its intended sensors aboard, LDCM earth-observation science data required a downlink information rate of 384 Mbps. This information rate, limited contact time, large file sizes combined with file compression served to stipulate that in order to survive logistically the mission must achieve a bit error rate (BER) less than $10^{-12}$. An additional complication was the physical constraint associated with the presence of the Deep Space Network (DSN) at 8400 MHz. The requirement here for both LDCM and DSN to co-survive was simply that that the power spectral flux density (PSFD) at the DSN antenna not exceed -225 dBm/(Hz $m^2$) from any potentially interfering source. In order to meet these restrictions and still satisfy the basic power requirements for maintaining a link, the LDCM spacecraft RF emissions must then be severely filtered. The maximum bandwidth that LDCM could occupy was 375 MHz, asymmetrical about an assigned carrier frequency of 8200 MHz. However, filtering not only truncates the transmission spectrum it also impresses significant amplitude and phase distortion on the link. What was not so obvious several years ago was how to select an appropriate high rate code from the available codes. The subclass of Euclidean geometry LDPC codes was just being promulgated by NASA as potentially useful for a wide range of space communication applications [1-4], several years behind its competitors of serially concatenated convolutional turbo-codes and DVB-S2. DVB-S2 concatenated a variable-rate

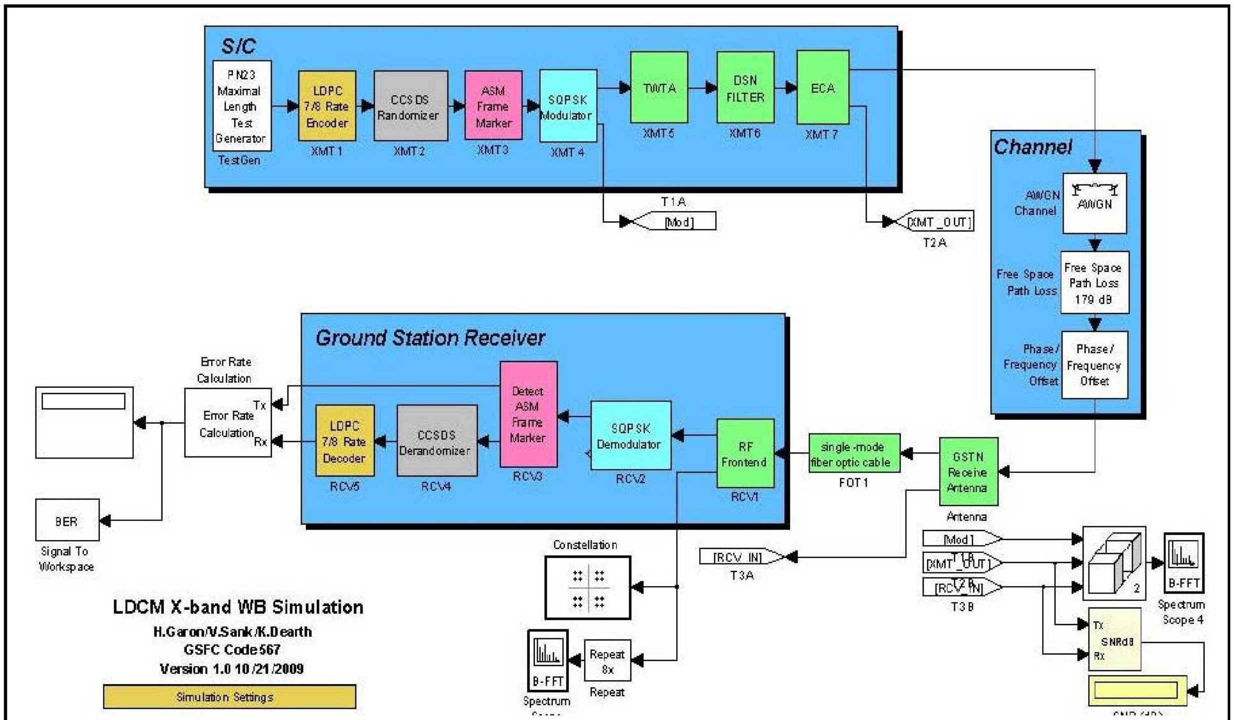


Figure 1. LDCM End-To-End Software Simulation.

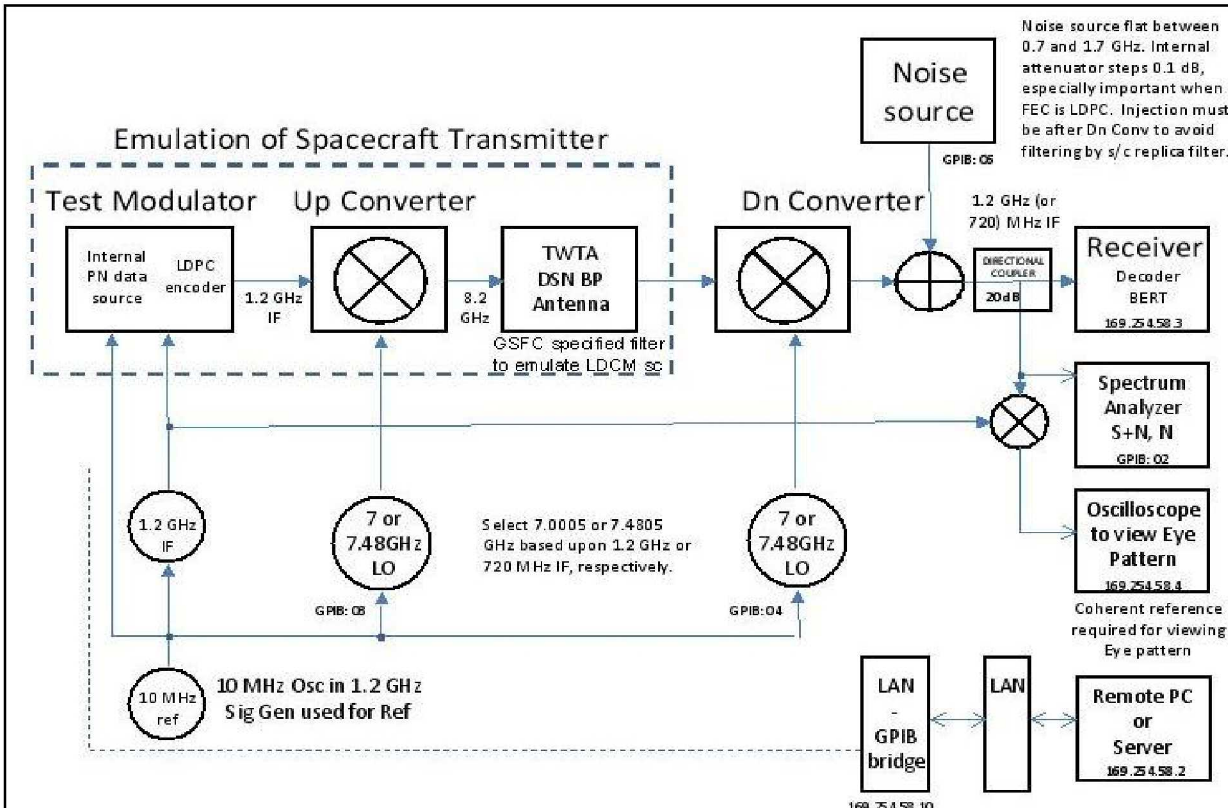


Figure 2. Block diagram of NASA/GSFC LDCM testbench.

LDPC code with an outer BCH code. The intent in both instances in combining codes was to remedy poor low error-rate performance.

On the other hand, LDPC 7/8 stood alone as a solution which not only met the high-data rate requirement but also did not exhibit a (known) error floor. Further, and conclusively, there was the immediate availability of flight encoders and ground decoders. Still, a 7/8 rate code with a 384 Mbps information rate leads to a symbol rate of 440 Msps. A good portion of the resulting offset QPSK (OQPSK) modulation spectrum which could have been transmitted must instead be suppressed by the spacecraft 375 MHz bandpass filter in order to satisfy the DSN spectral level requirement. The remaining central cause for concern in establishing link viability, then, may be directed at assessing the impact of this truncated spectrum along with the related and substantial distortions impressed on the link in both magnitude and phase.

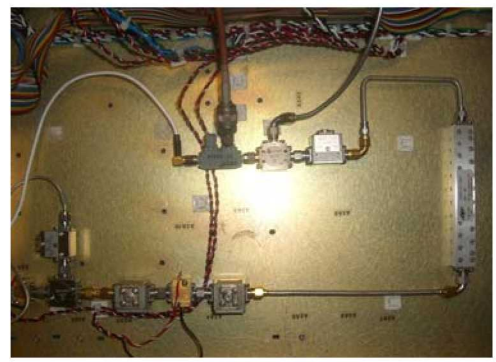

Figure 3a. Up/Dn converter depicted in the block diagram of figure 2b. The replica S/C filter is at the far right hand side.

**Link Simulation:**

To mitigate the risks that we understood and to better anticipate those risks still unknown to us, we simulated the entire link, end-to-end, in both software and hardware. Figure 1 shows the high level block diagram components constructed in software using Mathworks Simulink$^{tm}$. While the block diagram shown in figure 2 illustrates the overall functional breakdown of the hardware components. The key to the hardware simulation is an X-band bandpass filter (figures 3a and 3b), specifically designed to replicate the spectrum truncation and distortion produced along the analog portion of the RF link aboard the spacecraft (S/C). In the case of LDCM the filter embodies the combined impact on the link of the X-band transmitter, a traveling wave tube amplifier (TWTA), the DSN bandpass filter and earth coverage antenna. Referring to figure 2, in applying the S/C replica filter a test modulator first generates a 440 Msps PN23 data stream, LDPC 7/8 encoded, at 1.2 GHz. The 1.2 GHz output of the test modulator is up-converted to 8.2005 GHz and then applied to the S/C replica distortion filter. The output of the replica filter is down-converted back to a 1.2 GHz IF where broadband noise representative of the channel is injected. The consolidated signal with noise is finally presented to the input of a receiver. The testbench was intentionally designed to allow the IF frequencies at both input and output of the up/down converter to be independently varied. The local oscillators of the up/down converter can be adjusted so that any combination of test modulator or ground receiver can be employed in test. The link spectrum at the input to the receiver in simulation, prior to noise

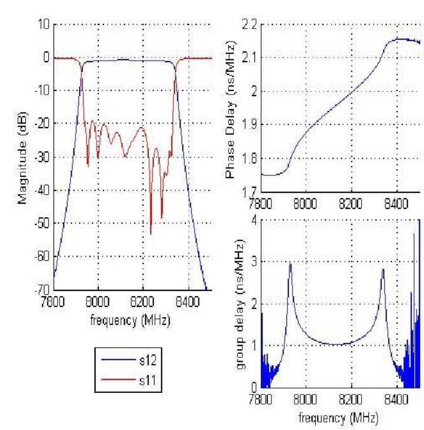


Figure 3b. Characterization of the S/C replica filter.

injection, is displayed in figure 5. To within the uncertainties of both the hardware and software simulations, the spectrum as presented to the receiver appears identical in both software and hardware.

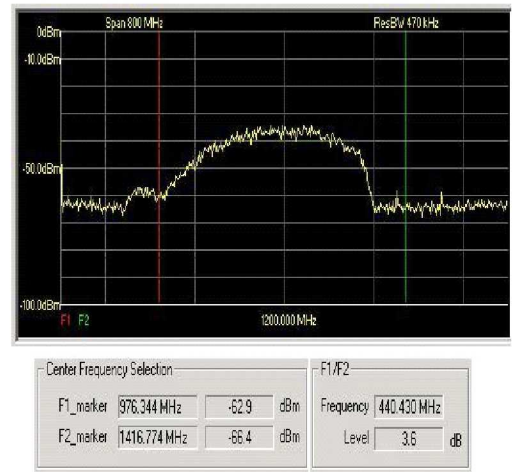


Figure 5. Emulated LDCM output spectrum, as seen by receiver, prior to noise injection.

**Results of the Software Simulation and Hardware Emulation:**
Using the hardware testbench as described above, we are able to demonstrate (figure 6) that a 7/8 rate LDPC encoded, 440 Msps data stream can be filtered with a bandpass of only 375 MHz and still be decoded with a BER of less than $10^{-12}$. Moreover, as can be seen from our results, this has been accomplished with minimal implementation loss, about 1 dB for the receiver shown here, and < 1.8 dB for other receivers tested. These observations indicate the link will function properly as presently designed and will meet the LDCM requirements. As a sidenote, the software simulation tended to be much more pessimistic than the hardware testbench. However, both the hardware and software properly emphasized that the success of the mission will rely critically upon the performance of the signal equalizer in the ground receiver. Both software and hardware have also indicated a particular sensitivity to the proper construction of the 1st stage equalizer filter, referred to by some receiver manufacturers as the receiver's matched filter. This filter is separate and distinct from the frontend filter. The frontend analog filter serves as an anti-aliasing filter for digital receivers. The 1st stage equalizer filter is synthesized totally in software and occurs after the conversion of the incoming signal from analog to digital. When dual equalizers are used, they may not both be adaptive. At least for one manufacturer's receiver we have developed a procedure to derive the coefficients of the matched filter by directly using the received input signal. Rather than having to anticipate any change in the communication link due to spacecraft component aging (or, for that matter, any reason), we simply "recalibrate" by regenerating the coefficients of the matched filter, then keeping them fixed.

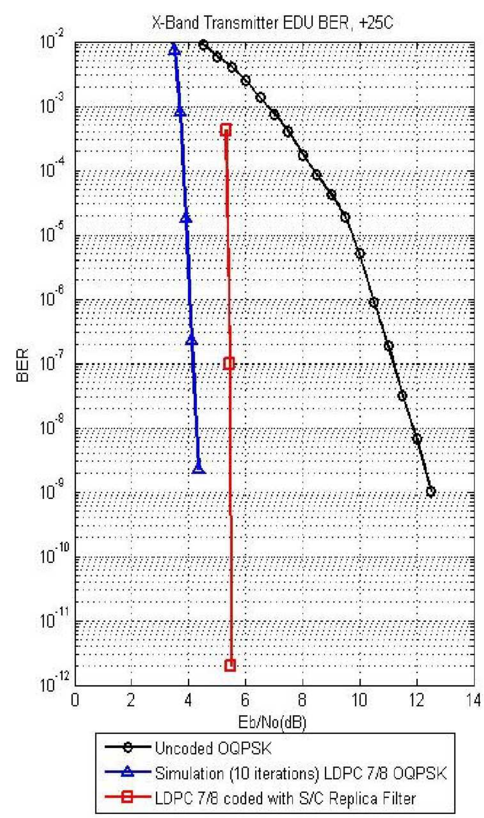


Figure 6. Measured results: Minimal implementation loss between replica filter and ideal, red and blue respectively.

**Equalization:**
The spacecraft filter is designed to truncate the bandwidth of the modulated spectrum prior to transmission so as not to violate the LDCM spectrum allocation adjacent to the DSN band. As discussed above, an undesired effect of the filter is that it introduces significant amplitude and phase distortion

in the data stream. The LDCM End-To-End software simulation model predicted that enough phase distortion would be introduced so as to make the communication link untenable unless the receiver equalization could compensate properly. All programmable high data rate (HDR) receivers use some form of equalization after conversion of the analog input signal to digital format. The goal of the equalization is to properly restore the spread of bit energy, the intersymbol interference (ISI), cause by hardware distortions. Some receivers capable of correcting significant and substantial magnitude and phase distortion on a link employ two stages of equalization. The 1$^{st}$ stage equalization equates to a matched digital receive filter embedded within a Costas loop of the demodulator and bit synch. The 2$^{nd}$ stage Adaptive BaseBand Equalizer (ABBE) which follows is generally double-blind and essentially completes a mop up action of the output of the 1$^{st}$ stage. The level of integration of these equalizers with the demodulator is so great that it is difficult to distinguish where the demodulator leaves off and the equalizers begin, especially since each interacts and impacts the demodulator so dramatically. These initial coefficients of both the 1$^{st}$ stage equalizer filter and the ABBE can be set by the user and stored as default. Together, both of these algorithms can compensate for large swings in amplitude and phase assuming that these occur within some consistency and, at not too high a rate. The receiver can automatically and continuously update the adaptive equalization stage coefficients to maximize performance.

**Conclusion:**

Coupled with a commercial ground telemetry receiver designed to do the LDPC decoding and to overcome the link distortions, we have able to demonstrate that we can maintain a viable 440 Msps link at BER less than $10^{-12}$ with an implementation loss of less than 2 dB, despite an asymmetrical truncation to a 375 MHz bandwidth. The BER and the ground implementation loss are both extremely low, in turn, maximizing the useful satellite contact time. Due to the availability of flight encoder chips qualified to Level 1 (GEO environment) and the availability of commercial receiver with decoders, it has turned out to be fortuitous that LDCM chose the LDPC 7/8 rate codec for their near-earth application. With the continual push for even higher data rates within an increasingly more crowded spectra we may anticipate the election of LDPC 7/8 as the codec of choice for many more high data rate near-earth missions in the future.

**Acronyms:**

| | |
|---|---|
| ABBE | Adaptive Baseband Equalizer |
| ASM | attached sync marker |
| BCH | Bose-Chaudhuri-Hocquenghem |
| BER | bit error rate |
| BERT | bit error rate test |
| BP | bandpass |
| CCSDS | Consultative Committee for Space Data Systems |
| codec | coder-decoder |
| dB | decibel |

| | |
|---|---|
| D-FFT | double Fast Fourier Transform |
| Dn | down |
| DSN | Deep Space Network |
| DVB-S2 | Digital Video Broadcast – Satellite, second generation |
| ECA | earth coverage antenna |
| EDU | engineering development unit |
| FEC | forward error correction |
| GEO | geostationary orbit |
| GHz | GigaHertz |
| GPIB | general purpose interface bus |
| GSTN | ground station |
| HDR | high data rate |
| IF | intermediate frequency |
| ISI | intersymbol interference |
| LAN | local area network |
| LDCM | Landsat Data Continuity Mission |
| LDPC | Low-Density Parity Check |
| LO | local oscillator |
| Mbps | Megabits-per-second |
| MHz | MegaHertz |
| Msps | Megasymbols-per-second |
| OQPSK | offset QPSK |
| PN | pseudo-noise |
| PSFD | power spectral flux density |
| QPSK | quadrature phase shift keying |
| RF | radio frequency |
| Rx | receiver |
| S/C | spacecraft |
| TWTA | travelling wave tube amplifier |
| Tx | transmitter |
| WB | wideband |

**References:**

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[2] Y. Kou, S. Lin and M.Fossorier, ”Low density parity-check codes based on finite geometries: a rediscovery and new results,” *IEEE Trans. Information Theory*, vol. 47, pp. 2711-2736, Nov. 2001.

[3]W. Fong, “White Paper for Low Density Parity Check (LDPC) Codes for CCSDS Channel Coding Blue Book,” CCSDS Panel 1B Meeting Paper, Sept. 2002.

[4] G.P. Calzolari and E. Vassalo, ” Combined Advanced Coding & Modulation for Future CCSDS High-Rate Missions”, SpaceOps 2006, 19-23 June, Rome, taly.