TELEMETRY (TM) HAS CHANGED QUITE A BIT OVER THE PAST 53 YEARS

A long time ago, way back in 1961, my very first job after college was with Vertol Helicopters (now a Division of Boeing) in Media PA. Our flight test facility was located on the East side of the Philadelphia International Airport and our tie-down facility was located in the swamps east of the airport where the mosquitoes zoomed in on us at night with all of the lights focused on us. The CH-47 Chinook flight test program was just starting and we were preparing and installing the instrumentation system. The number of measurements (MEAS) was in the high hundreds and the instrumentation system consisted of a photo panel, two CEC-124 oscillographs capable of recording 50 channels each using galvanometers to reflect light onto photographic rolls of paper. In addition we also had two CEC-119 36 channel oscillographs and a Brown temperature recorder with a thermos bottle ice bath reference. All MEAS except the thermocouples were wired to a centralized 4' by 4' patch-board so they could be selected and assigned to a recording device. Aside from the oscillographs we also had several banks of EMR (tube type) Voltage Controlled Oscillators that were used to record MEAS data on the AMPEX AR-100 analog tape recorder. Each VCO bank had a total of 14 channels of data and we utilized one of those 14 channel banks to modulate a Frequency Modulated telemetry transmitter. So in effect the combination of the FM VCOs modulating the FM XMTR created an FM/FM TM system. The ground station could receive and discriminate the FM signal and recover the 14 channels of data. Out of the hundreds of on-board recorded data only 14 MEAS could be looked at during the flight. In some respects this was a big breakthrough but at the same time selecting precisely what 14 MEAS could be monitored in the ground station, later called a Mission Control Room (MCR) was a difficult choice. Obviously the most critical data was sent on the TM link.

TM reception improves with altitude but helicopters fly low so we had a low power TM XMTR which was boosted with a high gain power amplifier. To test to see if the TM XMTR system was working I took a graphite pencil and held it close to the TM antenna. If it sparked we knew that TM was on and operating. Due to the nature of the electronics at the time (tube type technology) signal conditioning for the MEAS and the Excitation Voltage to the XDCRs there was some drift and gain changes that always had to be compensated for in order to get accurate data. Same thing held for the TM transmitter. We had to tweak the modulating signal so the XMTR would be properly deviated. There was no remote frequency select option so we had to install a set frequency tuning device. TM reception was fairly good even though the receiving antenna had to be manually operated. For unknown reasons at the time during some flights especially on Friday afternoons we would completely lose TM reception and since critical flight data was on TM the flights had to be aborted. When the helicopter was on its way back to base the TM signal would come back on. Eventually we took out the maps and traced out the flight path and saw that there was a big water tower out there and we determined that the pilot knew that if he hovered behind the water tower we would lose signal and terminate the flight. The pilot had long weekends planned and this enabled him to depart early on Friday.

In 1963 I joined Republic Aviation in Farmingdale L.I. N.Y. and went to work on the start of the F-105F, the first two seat F-105. I was assigned to assist in the development of the ejection seat sequencing and my particular job suited me very well because I worked on the dummies. Obviously you have seen the dummies that are instrumented and are used to simulate real people and are used for automobile crash

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evaluation. The task was to build up and test the instrumentation telemetry system built in to the chest cavity on the dummies. We utilized a bank of Voltage Controlled Oscillators (VCOs) with signal conditioning to acquire pitch and roll angle, three axis of acceleration and a few other MEAS. After we built up the first instrumentation package to be inserted in the dummy's chest cavity I was told to run environmental lab tests to see how well the instrumentation package with the TM XMTR would survive the environment of being ejected/rocketed out of the cockpit and then being hit with the forces experienced while travelling at 300 knots. I was given a list of frequencies and amplitudes to run a shaker table with. I mounted the instrumentation package on the shaker table and began the test. As time progressed I changed the frequency and amplitude and took notes. About halfway through the test I heard a ping and a bang followed by more violent noises and I immediately shut down the test. This was the last environmental test before the dummies were to be sent for ejection testing on a high speed sled and it appeared that I screwed up badly and most likely would be fired for being incompetent. It turned out that I was not at fault and that a faulty tie-down attach screw that was common to the VCOs and the TM XMTR failed well below the specified load factor. The test was rerun with improved screws and the system was accepted for use.

In 1965 while still at Republic Aviation I was assigned to Project Fire, a research and development program for reentry of the Space Shuttle into the Earth's atmosphere. We had a Nose Cone that was to be mounted on the top of an Atlas rocket on Pad 34 at Cape Canaveral. There were three outer shields on the nose cone that were heavily instrumented. As the nose cone re-entered the Earth's atmosphere data from the 1st shield would be telemetered to Mission Control Rooms at the Cape and at other facilities and was watched with a giant telescope on Ascension Island off of the African Coast. The telescope was equipped with a spectrometer which gave details about temperature and chemical composition. At a precise time the 1st shield was blown off with squibs and then the 2nd shield MEAS were taken and then the 3rd shield was exposed. We had conducted months of clean room testing of the instrumentation data acquisition system, Pulse Amplitude Modulation and Pulse Duration Modulation signal conditioning system and the TM transmitter and everything checked out well. PAM and PDM were used so that with the bank of Voltage Controlled Oscillator system we could acquire hundreds of temperature MEAS along with positional MEAS and transmit that data via Telemetry.

When the nose cone was shipped to the pad facility at Cape Canaveral we retested the nose cone system in our clean room. Things went well and the data obtained matched what we had acquired in Farmingdale NY. Then came the moment of truth when we closed the nose cone and telemetered the data to the ground receiving station that I was in charge of. The TM data was unintelligible and everyone asked me why my ground station was so screwed up. We went back over the operation that we had performed and as the nose cone was opened for inspection the TM data cleared up and it was once again perfect. Technicians slowly closed the nose cone and when they reached a certain angle the TM data went to pot again. Aha, we then came to realize that throughout all the months of testing in NY the nose cone was never closed. Now, with the scheduled launch date rapidly approaching a fix had to be made. All of the MEAS and signal conditioning were not the culprits. It turned out that the cause of the problem was the circular antenna that was around the nose cone radiated not only outward but also inward which created an electronic TM signal mess. One of our quick thinking engineers made a fast trip to the town of Cocoa Beach to a hardware store and brought back a roll of copper screening used for screen doors and windows. We looked at him like he had three eyes on his head and asked what he planned to do. The circular antenna was on the upper portion of the nose cone that opened up and the rest of the instrumentation equipment was on the base of the nose cone. He cut out a circular shape of the copper screening to cover the base where the instrumentation equipment was and attached it to a ground stud. He requested that I go back and man the ground station and look at the data as they closed the nose cone. This time the data started out good and stayed good throughout the closing and opening of the nose cone. The fix was documented and the USAF and NASA inspected what was done and gave us the thumbs up. TM was good and we got a go-ahead and prepared for the launch.

That was followed by an assignment in 1966 to work on the XV-5A a vertical lift off airplane based at Edwards, AFB CA on the Mojave Desert. A three company team had been formed with Ryan building the airframe, GE supplying the engines and fan ducts and Republic Aviation supplying the instrumentation. This was my very first hands on experience with a Pulse Code Modulation (PCM) system. If I remember correctly it could accommodate 80 MEAS. It had an eight bit Analog to Digital Converter (ADC) and the output signal was fed to an airborne analog recorder and to the FM transmitter. I had to learn all about the binary, octal and hexadecimal math systems and for our setup and calibration device we used an Airborne Single Channel Read Out (ASCRO) that we could dial in each MEAS channel one at a time and get octal count readout. An eight bit ADC produced a lot of stair case type data as there are only 512 counts to represent each MEAS. A flap angle of 30 degrees divided by 512 counts = .0586 degrees per count and likewise 30,000 feet of altitude /512 counts produced a resolution of 58.6 feet per count. Aside from the poor resolution due to the 8 bit ADC the concept was great and I could see and appreciate the potential of what this could lead to in the future. Little did I know at that time that the rest of my career would be focused on the use of PCM telemetry.

I left Republic in 1967 and went to work for Grumman at Calverton L.I. N.Y on the US Navy Version of the F-111. The instrumentation data system was on a pallet in the weapon bay and I had to learn how to do a duck walk. The instrumentation system was a pretty straight forward FM/FM system with banks of Proportional Band Width VCOs and signal conditioning to acquire lots of MEAS data. However the frequency requirements for many of the MEAS were too high for the PBW VCOs so we brought on the new technology of Constant Band Width VCOs. Now we could acquire MEAS data at much higher rates for accelerometers and other MEAS. The number of MEAS that could be transmitted to the ground station was still quite low so innovations were made but in essence we still had a FM/FM TM system.

The A6A Intruder instrumentation system was also a basic FM/FM system but in 1968 a breakthrough was made and it enabled us the transmit MIL-STD-1553 Multiplex Data at a high bit rate to the US Navy Patuxent River MD ground station. It was what is now termed full bus Chapter 8 data. There was no room left on the TM bandwidth for anything but the 1553 Bus data but it was a great success.

In 1969 Grumman decided to test out the concept of PCM versus VCO FM/FM technology on an actual A6A test aircraft. There were a lot of naysayers who were staunch in their belief that FM/FM was here to stay and PCM was never going to catch on. At the time aside from the engineers in the instrumentation Research and Development Lab I was the only INSTR Operations engineer that had any experience at all with PCM. So by default I was put in charge of setting up and running the side by side flight tests on A6A #7 and processing the FM data and the PCM data to show that the 12 bit ADC PCM/FM system was indeed superior to the VCO based FM/FM system. This was a time consuming and costly experiment but it paved the way for the next really big Grumman program, the F-14.

The changeover in 1970 for the F14 Flight Test program from the old VCO/FM/TM system to PCM/FM/TM was not an easy one as not only did the aircraft system have to change but the ground station for Real Time in-flight processing and Post Test Batch processing also demanded the use of all new equipment. INSTR personnel had to be trained in the use of PCM for on-board recording and for PCM telemetry. Many refused or were slow to learn the new technology and they got left behind. The new kids on the block, young Instrumentation (INSTR) engineers and computer programmers fresh out of college had no hang-ups about leaving one technology for another and quickly rose to the top and displaced many of the old stuck in the mud old timers. The airplane PCM system actually had two 12 bit ADC units because at its fastest rate one ADC could not keep up with the required MEAS data rate. The TM changed from handling 14+ MEAS in the Real Time environment to now handling thousands of MEAS. The MCR now contained monitors displaying Engineering Unit (EU) data and answers produced by processing a multitude of MEAS EU data through complex computer programs. The TM link was still a FM/TM XMTR but now the signal into it was PCM. This opened the door for ever the increasing the number of MEAS being accommodated along with the demands for higher and higher frequency response.

On the second flight of the F-14 I was out at the airplane with our lead INSTR engineer asking about how the preflight went and after the pilots boarded and got ready for take-off I went to the Grumman Advanced Flight Test Data System (AFTDS) facility adjacent to Plant 7 at Calverton L.I.N.Y and went up to the 3rd floor to take my INSTR Advisory seat close by to the test Conductor. We had a good TM signal and we looked at the airplane via a Zoom TV camera mounted on the TM tracking antenna. The take-off was smooth and after flying around for a short period of time things changed rapidly as the airplane hydraulic systems began failing. The airplane was heading back for an emergency landing and it was about a mile short of the runway when both pilots safely ejected and the airplane crash landed. We had witnessed an accident and we had TM data up until it crashed. Later on we retrieved the airplane PCM data and with the help of the FBI and some of their advanced techniques we were able to retrieve additional data from the partially scorched PCM data tape.

In 1978 I went to work for General Dynamics on the very early part of the F16 flight Test program at Edwards AFB CA. PCM/TM systems were in general use and remained fairly static in terms of growth or innovations and PCM was the most accepted means of acquiring flight test MEAS data. However, this was the first time that I ever got to be part of a Real Time Flutter Dynamics test program that had enough TM bandwidth and frequency response to be able to acquire all of MEAS needed for Flutter analysis. With Real Time processing of the TM data each test point could be evaluated and if safe to do so the pilot could continue on with the next test points.

In the early 1980s there were ten F16 flight test aircraft on our flight line and we ran a very busy schedule with at least 6 flights per day so it was very frustrating to preflight the airplane and the instrumentation and then go to the assigned ground station Mission Control Room to find out that the PCM data that was being received via the TM data stream was not showing up correctly on the various strip charts and displays. Day after day the MCR setup personnel would say that the airplane instrumentation was all hosed up. We knew this not to be true and we kept requesting them to check the raw PCM counts coming in to see if they were indeed locked onto our PCM stream and had a good bit synch, frame and sub frame lock. Eventually they would get their act together and we could be able to start our ground checkouts and then the flight. Then I devised a secret weapon in that I preprogrammed all the basic air data MEAS to known static PCM count and Engineering Unit Values on Format 2 of the airborne PCM system. So, when we TM'd the PCM data stream to the MCR there was no guesswork for the MCR personnel. They often asked how while the airplane was sitting on the ramp the data that was transmitted showed that it was flying at 400 knots at 30,000 feet and was pulling 2.5Gs. They never did catch on. Prior to flight we would switch the PCM/TM format back to Format 1 and continue on with a good data and a good flight.

There were oh so many times that we had to remind the pilots that Hot Mike was on and that everything that they heard or said was being recorded on board and transmitted over the air via telemetry to the MCR and a large audience. There were indeed some very embarrassing moments.

Starting in the mid-1980s the U.S. Government dictated that all flight Test PCM Telemetry data has to be encrypted and supplied us all with SP10-68 type encryptors. There was probably good reason for that action because years ago when I was at Cape Canaveral just prior to the launch a bevy of fishing ships equipped with large antennas would be lingering just off the coast so they could record and process our data. Years later I sat in the F16 Ground station and when we saw an F-15 takeoff we tracked it with our 4 foot dish antenna and I was able to determine their PCM bit rate, frame rate and subcom level. Once I had locked onto the F-15 8 bit PCM data I was able to determine which PCM channels were moving at a faster rate than others and I could virtually tell what MEAS were on what PCM Word and Frame. With a little more time and patience I myself would have been able to deduce Engineering Unit data for many of the MEAS. If a novice like me could get that far you can imagine what Russian scientists could do. Therefore it became obvious to all that our Telemetry data must be encrypted.

By 1987, I moved on to join Lockheed and immediately became involved in the YF-22 vs. YF-23 fly off competition. The big change in instrumentation at this time was that Aydin Vector designed and built micro miniature PCM signal conditioning units that could be distributed throughout the aircraft close to the XDCRS and sensors. Prior to this the wiring for every MEAS had to be brought to a centrally located PCM system. PCM frame sizes increased to accommodate more and more MEAS. The signal conditioning became more stable and allowed for more accurate data. More MEAS at higher sample rates meant there had to be an increase in Telemetry bandwidth and we went from a typical average of 400K bits per second up to 5 times that at 2 Megabits/second. Selection of MIL STD 1553 MUX Bus Message data into the TM PCM stream (known now as IRIG 106 Chapter 4 PCM) also became crucial so that Avionics personnel could see how their systems were performing in a Real Time environment. The standard analog XDCR data was 12 bits but the MUX Bus data was 16 bits long and some of the MUX Bus Messages were 32 bits or 64 bits long. The demand for MUX data on the TM data stream kept on growing.

After the award of the Advanced Tactical Fighter (ATF) program was announced I advanced to be the Manager of Flight Test INSTR for Lockheed in Marietta GA and we were teamed with General Dynamics and Boeing. We each built different sections of the airplane and then it was joined together in Marietta GA. The MEAS requirements list for the F-22 was at least a magnitude higher than any previous programs. That forced us to introduce the use of two 5 Megabit PCM/TM streams for many of the F22 Test airplanes. We used up so much telemetry bandwidth that we essentially boxed out other test programs from scheduling test flights on the L- Band frequencies at Edwards AFB.

At the very start of the F22 program there was some concern raised about the ability of the TM data to be received at the MCR because we were using a Low Observable INSTR L Band antenna. One of the AF INSTR engineers wrote a paper as part of his Master's degree requirement and he claimed that we could not fly past 50 miles at 30K feet. He had a long and well done dissertation and used all the proper technical terms and had lots of fancy equations which I could not follow. To test the theoretical vs. reality I requested that we commandeer a company Beechcraft Bonanza and mount the LO L Band antenna on the bottom surface of the airplane and power that with a small PCM system sending its signal to our 10 watt TM transmitter. We plotted out a course and retained radio contact with the MCR and flew the route and altitudes that we had preplanned. We reached the point in the sky where the theoretical study said that we should lose signal and we kept on going. We tripled the predicted good signal distance and returned to base. It turned out that the technical study had every point; transmitter, cables, connectors, transmitting antenna, receiving antenna, cables, connectors and TM receiver, at its worst case and when all the points were added together it spelled out doom. Well, needless to say practical won out over theoretical and it made my day.

During F-22 low and medium taxi runs on the field in Marietta GA the aircraft ran along in front of a number of hangars and as a result we got a lot of TM Ground bounce effects which really disturbed our ability to lock onto the PCM data. Losing synch created all the strip chart pens in the MCR to chatter so loud we thought that the fire alarms were going off. Our solution was to call back to Edwards AFB in CA and ask for help. They immediately supplied a team of personnel equipped with a Re-Rad system that could be deployed out on the field so that they could pick up the aircraft TM signal with no ground or background clutter effects and transmit that TM data directly at our TM receiving antenna on the top of the immense C5-A hangar. It worked like a charm and saved us time, effort and much embarrassment.

On the morning of September 7th of 1997 I had my entire Instrumentation and Data Processing crew of Engineers and Software programmers primed and ready for the big event to take place. We all went to our assigned posts and stations and we completed the pre-flight checkout along with checking the TM data stream to the ground station Mission Control Room. The chief test pilot, Paul Metz, fired up the engines and after a long and thorough checkout he was given the sign to taxi. I was in direct contact with many of my INSTR engineers and MCR operators with a hand help radio. When the aircraft taxied to the runway and the engines were run up I turned to look at the MCR TM receiving antenna and I noticed that it was pointing in the wrong direction, away from the aircraft. I yelled over the radio to the MCR that they were apparently locked in to a TM signal that bounced off one of the buildings adjacent to the runway. I was afraid that we were going to lose signal and the MCR personnel would not be able to track the airplane and get good PCM data but for some unexplained reason they did not miss a beat.

The takeoff and in flight data was good throughout the flight. This does help to explain why my hair turned from black to snow white since this was just another one of the high panic, adrenalin flowing moments. I dare not mention all of the other close incidents we had over the years.

At long last in 2000 I got to work for Northrop Grumman on the B2 Flight Test Program and now I simply stand in awe every day when I come to work. My first task was to convert the INSTR system over from a company R&D developed Northrop Grumman Data Systems 3000 to a commercially built ACRA based PCM system. The NDS system was well designed and performed admirably but parts were becoming obsolete and it was difficult to maintain the system. The ACRA PCM system would up being one fifth the size and appreciably lighter and more efficient. One of the best features was that it had a 16 bit ADC for the PCM and that provided 8 times the 12 bit resolution and the analog PCM MEAS and the MUX 1553 MEAS were both 16 bits long. The B2 Engineering Modification Design program was well over and as such most of the Flight Test Data being acquired was from the many MIL STD 1553 MUX Buses on board. Later on we added a few high speed standalone PCM systems. The PCM TM system used to acquire data for the Mission Control Room Engineers has a low rate of 1.5 Megabits per second because most of the Avionics Messages on the Busses is sampled at relatively low data rates. A second TM data steam is used for High Speed PCM data or video data at 5 Megabits per second. A recent innovation for the B2 Telemetry streams is the use of SOPQSK technology which greatly reduces the TM bandwidth usage.

In 2010 on another Northrop Grumman Program they started using an Ethernet Based PCM system and looking over their shoulder we can see that this is a paradigm shift from where we have been heading and it appears to have many advantages over how we handle INSTR data today on B2. There are some immediate benefits in how MEAS are selected for recording on-board and for TM to the MCR. Being able to carry and switch PCM TM formats to be aligned with the flight card requirements is a big positive and so is the manner in how real time and post flight data can be processed without the use of expensive front end equipment. The door to greatly improved Telemetry methods is opening once again and we are looking to future enhancements in the field of Telemetry.

Things That Are Better Today for Telemetry

- No longer require pre-modulation adjustments
- Frequency selection can be remotely controlled
- Increased Reliability, lower MTBF
- Increased Stability, no drift
- Reduced size, weight and power requirements
- Increased bandwidth utilization with SOPQSK
- Easier setup, Lower cost and requires fewer personnel to operate and maintain

Things That Are More Complex today for Telemetry

- Security Levels
- So much data is being telemetered that it is hard to know all the MEAS on an individual basis
- More data sources than before; Orange Wire MEAS, Bus Messages, Video, Fiber and Ethernet