END-OF-LIFE INDICATORS FOR NIMA'S HIGH-PERFORMANCE CESIUM FREQUENCY STANDARDS

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Abstract

The National Imagery and Mapping Agency (NIMA) operates a worldwide network of GPS monitoring stations that utilize high-performance cesium frequency standards and geodetic quality GPS receivers. The NIMA Monitor Station Network (MSN) operates continuously, and has been in operation for more than 7 years. The frequency standards are located in non-laboratory environments and logistically challenging locations. The mean lifetime of the cesium-beam tube (CBT) is approximately 6 years; failure or end-of-life of the CBT is a significant cause in the reduction of data used to produce the NIMA GPS precise ephemeris.

This paper considers methods of predicting CBT failure and end–of-life by examining a variety of data, collected over a 7-year period, by the NIMA MSN. Several operational parameters that are available from the frequency standard hardware, which are routinely collected by the NIMA GPS Monitor Station Control Center (MSNCC), are examined. The relative clock phase of the frequency standards in a zero-baseline configuration (in the stations that have redundant hardware) is also considered as a predictor, by using GPS carrier-phase time transfer techniques.

INTRODUCTION

Today the National Imagery and Mapping Agency (NIMA) operates a globally distributed network of 13 unmanned automated GPS monitor stations. The primary mission of the monitor station network (MSN) is to collect observations from the GPS constellation. These observations, in conjunction with observations provided by the GPS Operational Control Segment (OCS), are used to compute the NIMA precise ephemeris and clock information for all the GPS satellites.

Each station incorporates a suite of equipment that includes geodetic-quality GPS receivers and high-performance cesium frequency standards (CFSs). Six of the 13 stations have redundant GPS receivers and CFSs and are referred to as Core Stations. Five stations are configured with a single GPS receiver and CFS, and are called Augmentation Stations. These 11 stations are the active network and contribute to the precise ephemeris production. The last two stations are used for testing and training and generally do not contribute to the precise ephemeris production.

In both configurations, Core and Augmentation, a single CFS provides a 5 MHz frequency reference to a single GPS receiver. All station equipment including the CFS is rack-mounted in standard equipment racks and located in general office space. No special consideration has been given to environmental control of the CFS or the GPS receiver other than what is provided by the local facilities, which includes temperature control of approximately $\pm 3^{o}$ C.

All of the active stations are located outside CONUS with the exception of the USNO station. This globally distributed network makes replacing a CFS that has reached end-of-life time critical, especially for the Augmentation Stations that only have a single standard. Shipping a new CFS to a station can take from one to two months. This prolonged shipping time has generated an interest in finding ways to predict the end-of-life for the cesium-beam tube (CBT) and has motivated this study.

The CFS used at each station is an Agilent 5071A with the high-performance CBT option, model 10891A. This device provides a means of outputting critical parameters with regards to its operation via an RS-232 serial interface. The parameters listed in Table 1 are generated every 15 minutes, collected in a daily event file, displayed on a status screen, and archived for later analysis.

Table 1

Ion Pump Current	Loop Signal Gain
CBT Oven Voltage	CFS Internal Temperature
Oscillator Oven Voltage	RF Amplifier 1 Gain
C Field Current	RF Amplifier 2 Gain
Electron Multiplier Voltage	Operation Status of the CFS

Currently the MSN has a population of 22 Agilent 5071A CFSs. Of the 22 CFSs, 11 have reached CBT end-of-life. Two of the 22 are still running with 7.33 and 7.5 years of operation on their respective CBTs. The NIMA CBTs have had life spans ranging from 5.67 years to 7.5 years, with the mean life span being 6.56 years with a standard deviation of 0.57 years. The sample size included the 11 CBTs that reached end-of-life and the two still running. One CFS that had a premature end-of-life at 3 years was not used in the statistics. NIMA's CBT lifespan compares to the manufacturer's mean life span of 6.34 years with a standard deviation of 0.55 years **[1]**. Figure 1 gives a distribution of the age of the CBTs at end-of life and also includes the two CBTs over 7 years old.

CESIUM-BEAM TUBE END-OF-LIFE

There are several factors that determine the life span of the CBT used in the Agilent 5071A **[1]** and they are:

1. Tube contamination
2. Hot-wire ionizer
3. Ion pump

4. Electron multiplier
5. Cesium supply

Of these factors, most end-of-life conditions can be attributed to either the electron multiplier or the cesium supply. The electron multiplier has an approximate design life of 25 years when operated at 100 nA, and the cesium supply used in the high-performance tube has a design life of approximately 7.5 years **[1]**.

The electron multiplier voltage (EMV) provides an indication of both the condition of the cesium supply and the electron multiplier. Because the cesium supply has a shorter life span than the electron multiplier, any increase in EMV to maintain a 100 nA beam current is a good indicator of cesium supply, provided the standard is operating normally. In addition, the EMV is one of the parameters monitored from each CFS at each station and, therefore, is the first method studied to predict CBT end-of-life. A typical EMV plot over the life of a CFS is shown in Figure 2. Once the EMV reaches a maximum of 2553 V, the loop signal gain is increased to maintain a 100 nA beam current **[2]**. For NIMA's purposes the end-of-life is defined as the point when the EMV reaches 2553 V.

EMV AS AN END-OF-LIFE PREDICTOR

For this study the EMV for 10 of the 11 CFSs that have experienced CBT end-of-life were collected from the data transmission packets archived at the NIMA MSNCC. The EMV data used in this study were from the end-of-life date back to 1 Jan. 2000. The plots show a subset of these data, which in most cases consists of the 100-day period preceding end-of-life. In addition, GPS phase data for the same time period were collected from the Core Stations, so that a frequency offset could be plotted. The Augmentation Stations only show EMV versus MJD because of the single GPS receiver and standard configuration.

This first item noticed in all the EMV plots is that there is a point when the EMV increases very rapidly to the maximum of 2553 V in a matter of days. These few days will be called the end-of-life period. Prior to this period the EMV has a small positive slope. Further investigation shows a unique structure in the EMV plots; there appears to be very small jumps in the EMV 19 to 50 days prior to the end-of-life period. This EMV jump is anywhere from 3 to 10 V in 1 or 2 days. Discussions with the USNO Alternate Master Clock station revealed that USNO has also seen a small jump in the EMV in 10 out of their last 11 standards that have reached end-of-life **[3]**.

This small jump in EMV can be seen in Figure 3 and 4, which are EMV plots for two different standards located at the St. Louis station from two different time periods. (The St. Louis station is a core station, except that there is only a single frequency standard.) Figure 3 shows a 5-volt jump in EMV from 52197 to 52199 and Figure 4 shows a 10-volt jump in EMV on 52365. These EMV jumps occurred 42 days and 53 days, respectively, prior to the end-of-life period. In Figure 5, the EMV plot shows a 6-volt jump 41 days prior to the end-of-life period for the standard, at MJD 52194, in Ecuador. There is also a dip in the EMV on MJD 52218; the reason for this dip is unknown and has not been seen in any other data. The standard in UK (Figure 6) shows two jumps in EMV, a small 3-volt jump 52 days prior to end-of-life on MJD 51985 and a large 8-volt jump 19 days prior at MJD 52018. Figure 7 is of particular interest because it shows two standards at the Australia station reaching end-of-life within 50 days of each other. Again there is a jump in EMV for Standard #1 37 days prior to end-of-life at MJD 52135 and Standard #2 19 days prior to end-of-life at MJD 52095. Although Standard #2 shows a large jump only 19 days prior to end-of-life, there is also a much smaller jump 52 days prior to end-of-life.

PHASE TIME TRANSFER AS A END-OF-LIFE PREDICTOR

GPS carrier-phase time transfer was also investigated as a possible predictor of CFS end-of-life, using the carrier-phase measurements of the receivers that are driven by these frequency standards. Because the core stations have redundant hardware, namely dual receivers and frequency standards, fed by a common antenna, we were able to compute relative clock phase and clock frequency between the two standards (one near end-of-life and the other normal). We used a double difference carrier-phase estimation program **[4]** in a zero-baseline configuration, in which baseline-dependent errors, such as atmospheric delays and orbit errors, are ignored. This technique could, in principle at least, be used over long baselines, namely between MSN stations, to perform the same test.

The results for the relative clock frequency of normal and failing standards are shown in Figures 5-7. During the period of normal operation of both clocks, noise in the frequency is at about $9?10^{12}$. At the onset of end-of-life, this clearly rises very quickly to significantly higher levels.

The example from Australia in Figure 7 requires some explanation, as it shows an increase after the failure of Standard #1 at about MJD 52112, but then decreases significantly, to just a few parts in 10^{12}, 4 days later at MJD 52116. The frequency undergoes some variation over the next 32 days, but then at MJD 52148 it returns to the normal level of about 9 parts in 10^{12}. Then Standard #1 fails at MJD 52155 and the characteristic increase in frequency is seen. This behavior can be understood from the maintenance records, which show that on MJD 52116, after the failure of Standard #1 was discovered, the feed from Receiver #1 was transferred to Standard #2. Then, on MJD 52148, after the replacement frequency standard was received, the feed from Receiver #1 was returned to (the new) Standard #1. Then Standard #2 failed. Thus, two receivers were driven by a single common frequency standard during the period of very low relative frequency offset from MJD 52116 to MJD 52148.

Unfortunately in all these data we were unable to see any indication of an appreciable change in the relative frequency of the clocks at any time prior to end-of-life, including at the time of the jumps in the EMV that have been noted above. A more in-depth analysis of the clocks stability during these periods may show an appreciable change; further study is needed. Thus, using the carrier phase as an indicator of CFS end-of-life does not appear promising.

CONCLUSION

From our study it can be shown that the mean life span of NIMA's CFSs is 6.56 years with a standard deviation of 0.57 years. In addition, the study shows that of the 11 standards that have reached CBT end-of-life, 10 showed a jump in the EMV 19 to 50 days prior to end-of-life. This small jump in EMV lends to development of a detection algorithm. Software could be written so that detection of this jump would be automated and warn network operators that a potential pending CBT end-of-life is near and arrangements could be made to ship a replacement standard.

Although the frequency offset data did not seem to predict a CBT end-of-life, more analysis needs to be performed. One area of future work would be to determine the stability of these CFSs as they approach end-of-life.

ACKNOWLEDGMENTS

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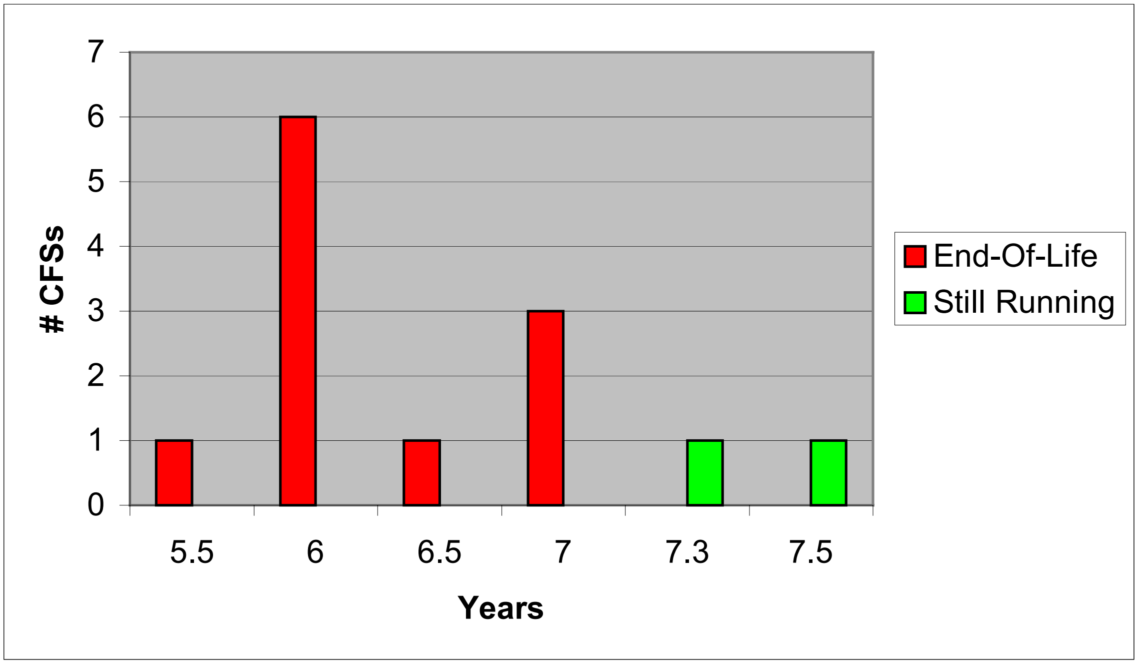

Figure 1. Distribution of CBT end-of-life.

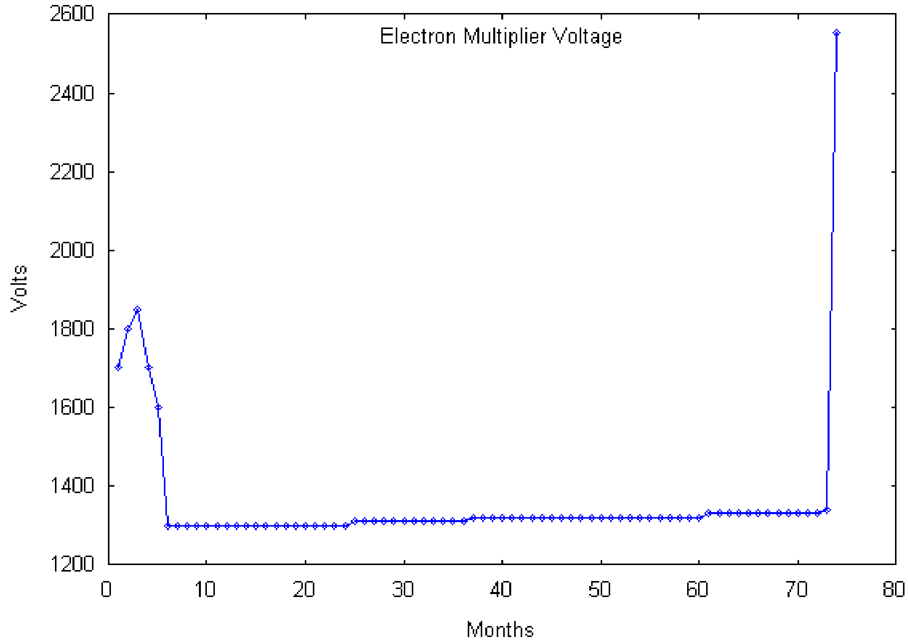

Figure 2. Typical EMV over CBT lifespan.

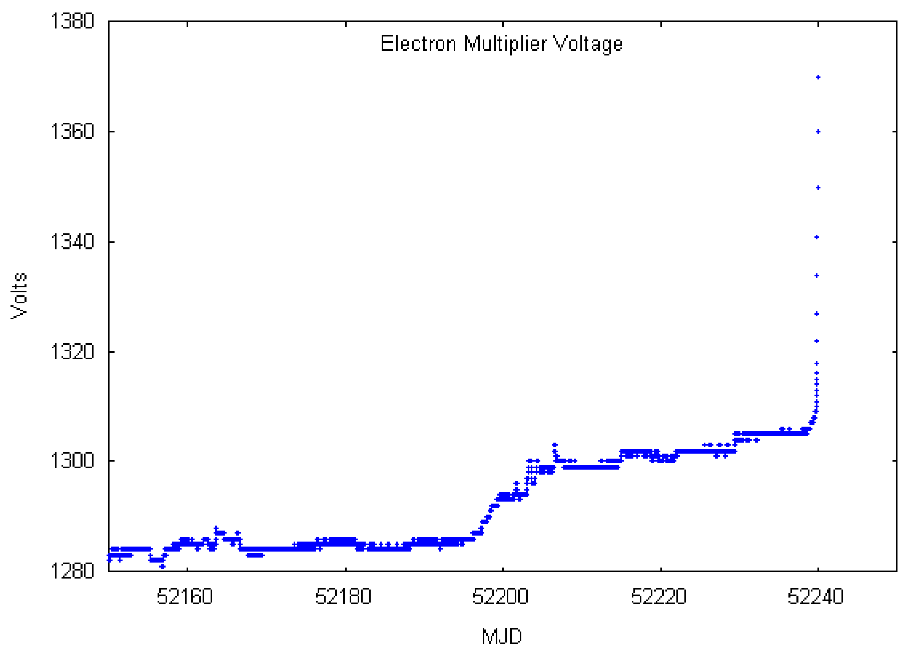

Figure 3. Cesium #1, St. Louis S/N3249A00675.

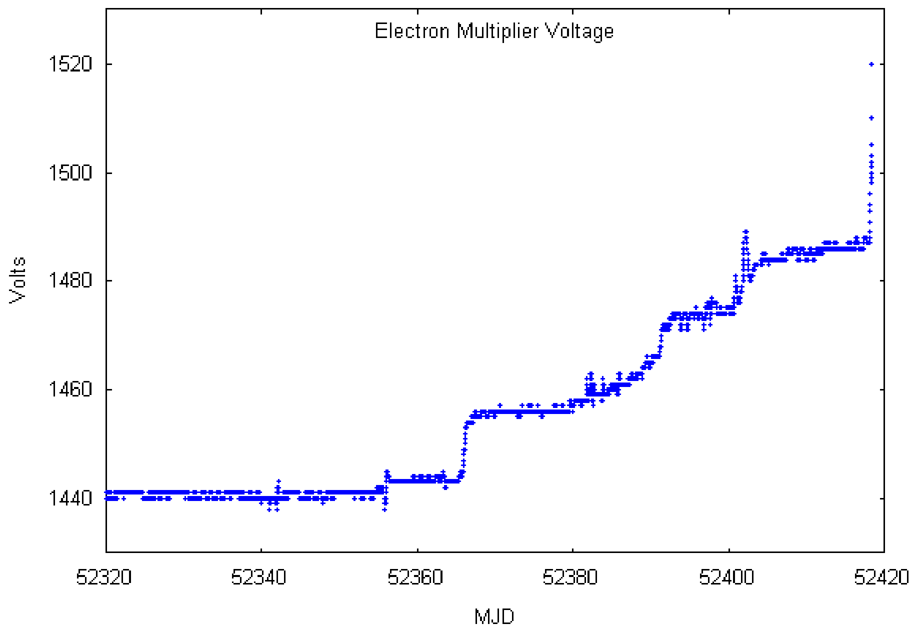

Figure 4. Cesium #1, St. Louis S/N 2149A00659.

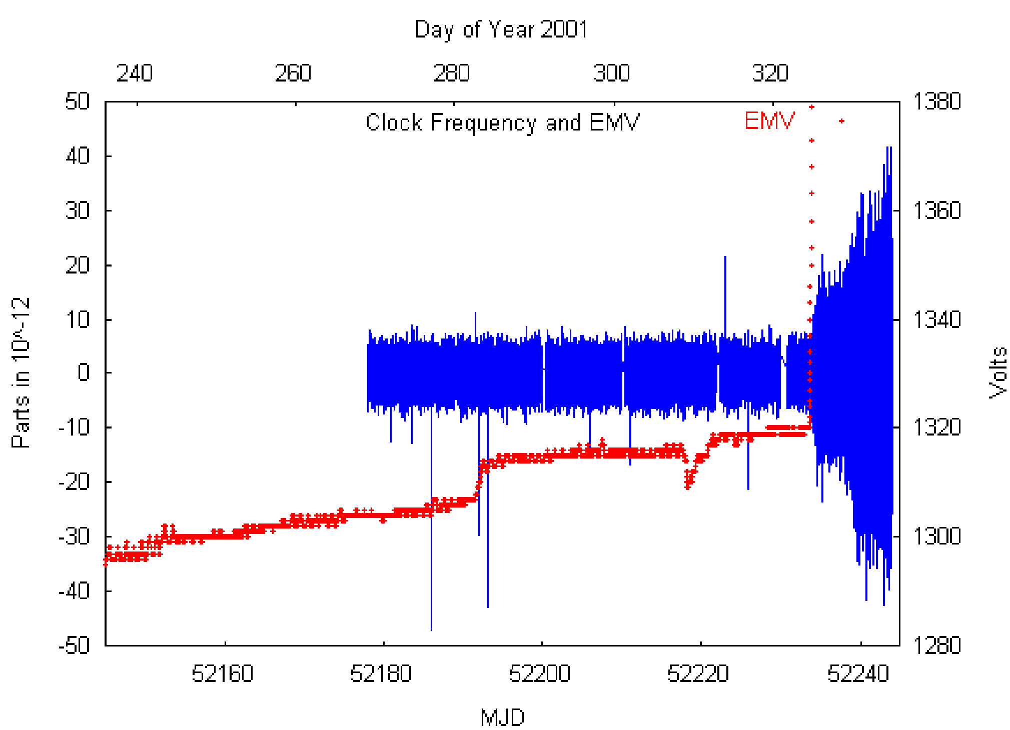

Figure 5. Cesium #2, Ecuador S/N 3249A00702.

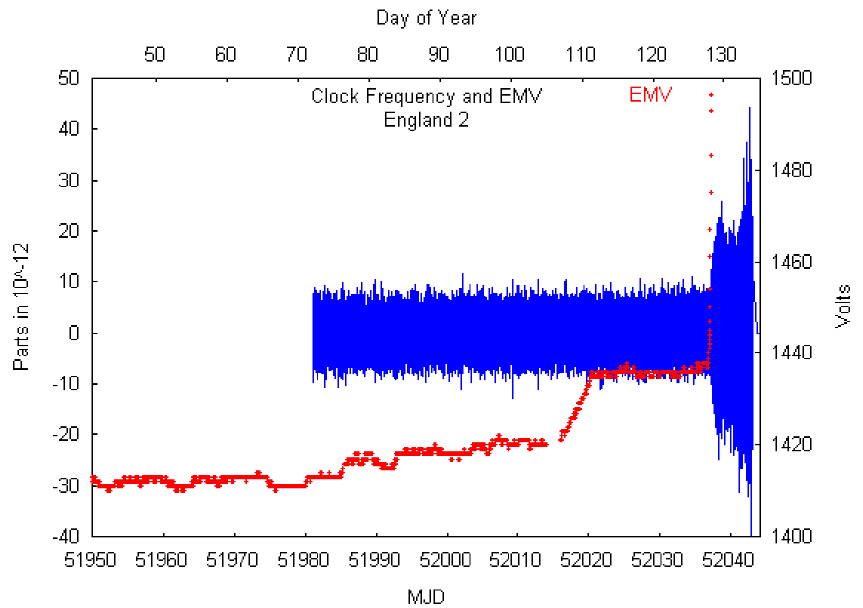

Figure 6. Cesium #1, UK S/N 3249A00576.

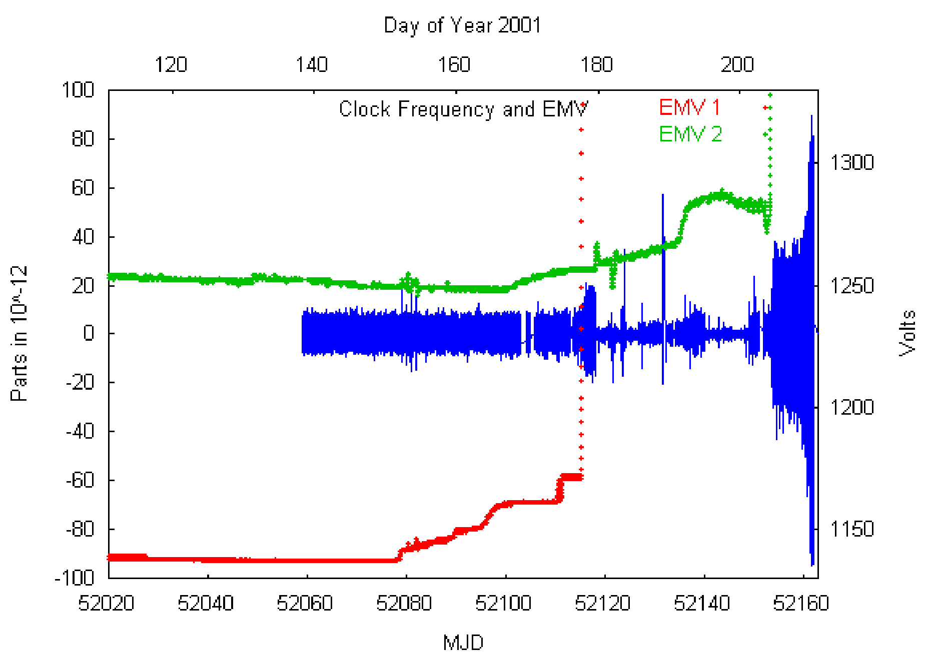

Figure 7. Cesiums #1 and #2, Australia

QUESTIONS AND ANSWERS

SIGFRIDO LESCHIUTTA (Istituto Elettrotecnico Nazionale): Have you any idea concerning what the physics could be behind the jump of the voltage of the electron multiplier?

CHRIS BROCK: I haven't looked into it, but I think there are other people who have looked into the physics of it.

JACK KUSTERS (Agilent Laboratories): I have been working on the cesium standards for the last 38 years, and hope to retire next month. We've seen something similar to what you've described, and we have always postulated that it probably is that at this point the liquid pool of cesium in the oven has finally reached its depletion of liquid cesium. From this point the tube is working on scavenged cesium from the oven walls, the body, the gaseous pressure that is still left inside. We've always defined end of life exactly the way you do. When the electron multiplier voltage starts climbing rapidly, you are out of cesium. There is just nothing left. So we concur with your conclusions.

STEVE HUTSELL (Second Space Operations Squadron): Do you have any insight or comparison or contrasting to some of the results that Harold [Chadsey] and Tony Kubik saw?

BROCK: No, actually I asked Bill Bollwerk for some data and charts or whatever. He hasn't sent me the data, so no, I have not.

HUTSELL: Some of it may reinforce what we've seen in the past. Some of it may offer some new insight because you are working in different environments.

BROCK: Yes, correct. We are in a different environment. And that was, again, one of the reasons we looked at what our life span was compared to what Agilent had published. We wanted to make sure we weren't doing anything negative to the tubes. They are in a rack and one is almost in an elevator shaft. They are in very different environments.