Perspectives on the Development of Commercial Cesium Beam Clocks

Dr. Leonard (Len) S. Cutler and his team at HP did outstanding work to remove the systematics and optimize the performance of their HP 5071-A cesium-beam atomic clock. On an ADEV diagram it behaves with the ideal white-noise FM over many decades of averaging times. Timing centers all over the globe have purchased this model because of the outstanding performance, and today the vast majority of some 400 clocks contributing to TAI and UTC are this kind. It was the first atomic clock that one booted up! When they first developed it, Len brought one to me in our lab in Boulder, and I was privileged to document its amazing performance. It was exciting to watch it turn-on (cold-start) and see the software learn all the lessons needed -- including magnetic-field compensation. It came on frequency in minutes with an accuracy as good as the NBS primary cesium-beam frequency standards of recent vintage. A paper presented and published in the Proceedings of the Fifth Symposium on Frequency Standards and Metrology, Woods Hole, MA, October 1995 by Allan, Lepek, Cutler, Giffard, and Kusters: "The Impact of the HP 5071A on International Atomic Time," shows the outstanding performance of the 5071A cesium-beam atomic clocks.
https://apps.dtic.mil/dtic/tr/fulltext/u2/a518478.pdf

We worked with Len and his team at HP over several years. Len had all the software in his laptop for the 5071A, I am guessing they had been working on the ideas for it for about eight years.

Len and I go back a long way. In 1964, he and Al Bagley developed the HP 5060A cesium-beam clock, and NBS bought several of those for our time-scale ensemble. Len later upgraded that technology to the 5061A. In 1991 HP introduced the remarkable performance of the 5071A. Len visited the lab in Boulder often, and we would see each other at the annual FCS and PTTI meetings. He was often my jogging partner at those meetings, and I would often go out to dinner with the folks from HP. For a time, the HP frequency standards efforts went with Bomac in the Boston area. Len moved back there for a time including his grand piano; he was an excellent pianist. David Glaze, who designed NBS-4, worked with HP and then Bomac in its construction, and I remember Dave driving across the country with that standard in tow.

When Len, Robin Giffard and team pulled together the 5071A, it was an optimization of the best chemistry, electrical engineering, mechanical engineering, physics, and computer software and hardware. The first cesium-beam atomic clock to be booted up, and in the process addressing how to make it be as accurate and stable as possible. Len addressed all the accuracy questions except the microwave cavity shift, and he was working on that one, which would have turned it into a primary standard.

There is a basic model for time dispersion in a clock. This equation is idealistic, but we have found it extremely useful over the years. GPS uses it to estimate the error of each of the SV clocks against GPS time, which is nominally synchronized with UTC(USNO) -- avoiding leap-second adjustments that are made to UTC to chase earth time. Since the only clock giving you correct time is the one you define to be so, you can think of this equation describing the error of any clock. First, you have its synchronization error, xo. Then you have its syntonization error, yo multiplied by t. Then you have the frequency drift (D), which exists in essentially all commercial standards with a time-error-dispersion rate going as Dt^2; this term is clearly the most dispersive in long term.

The frequency drift of the 5071A clocks is extremely small because of how well they dealt with the systematics. Len Cutler, Bob Kern and I once made a formal recommendation to GPS folks to use the concepts incorporated in the 5071A along with the excellent design of the space qualified cesium standard that Bob had made at FTS, and which became the first GPS cesium-beam clock. We did this because of the excellent low frequency drift properties of this design. The short-term stability is not as good as the GPS rubidium gas-cell clocks being used, but would have been good enough for operations to have good Kalman filter estimates. The big advantage of this approach is avoiding the drift term error which grows as time squared. This has very important tactical advantages. The last term in the equation is the model for all the residual noise variations of the clock, which can be both random and systematic -- like temperature effect variations. A basic message is that removing the systematics from a clock can make an enormous difference, and it is most efficiently done in software.