ATOMIC CLOCKS RESEARCH AT THE AEROSPACE CORPORATION

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Abstract

To satisfy the technology needs of US national-security space, The Aerospace Corporation maintains experimental and analytical efforts spanning the full range of precise timekeeping issues associated with space systems. Consequently, The Aerospace Corporation's laboratories are involved in the development and testing of timekeeping algorithms for diverse space missions, as well as research and development regarding the electronics and atomic physics of present-day and next-generation spacecraft atomic clocks. Here, we provide a brief overview of the work that is presently underway in The Aerospace Corporation's timekeeping laboratories.

INTRODUCTION

The Aerospace Corporation operates a nonprofit Federally Funded Research and Development Center (FFRDC) whose primary customers are the US Air Force and other government agencies. With its corporate headquarters in southern California, The Aerospace FFRDC provides scientific and engineering support for launch, space, and related ground system mission elements. Today, The Aerospace Corporation employs roughly 4000 individuals, over 2500 of whom are members of the technical staff. The technical staff's expertise spans a broad range of disciplines reflecting the wide range of technologies that are required by modern space systems. These include diverse areas of physics, chemistry, engineering, and mathematics. More than 2/3 of The Aerospace Corporation's technical staff have advanced degrees with about 30% holding a doctorate in their field.

To accomplish its mission of providing independent technical and scientific research, development, and advisory services to national-security space programs, The Aerospace Corporation is somewhat unique in maintaining a fairly large laboratory research capability. The corporation's laboratories employ about 170 Ph.D. scientists who carry out research and development in fields ranging from astrophysics and space sciences to materials science to atomic and chemical physics. Further information on The Aerospace Corporation's R&D activities can be found at the corporation's web site: *www.aero.org*, where detailed reviews of the corporation's research and other activities can be downloaded via the corporate magazine, Crosslink.

RESEARCH INTO PRECISE TIMEKEEPING

APPLIED PHYSICS

In very broad terms, The Aerospace Corporation's efforts in precise timekeeping divide naturally into applied physics and basic physics. In the area of applied physics, we are involved in the analysis of on-orbit timekeeping **[1]**, where we have done work examining how crystal oscillators and atomic clocks respond to the enhanced space-radiation environment associated with solar flares **[2,3,4]**. We are also involved with the development of "smart clocks" for space systems **[5]**, which are applicable to GPS integrity monitoring. By smart clocks, we mean atomic clocks that can sense their own operation without ground intervention, and in the case of a system like GPS, can autonomously take themselves out of the system if a problem is detected. Additionally, The Aerospace Corporation has the capability to fully characterize atomic clocks and crystal oscillators in order to assess their viability for space systems, and we routinely do this type of work in collaboration with DoD contractors, since (as a non-governmental entity) the corporation can enter into non-disclosure agreements with for-profit companies. Finally, we are routinely involved with the design and testing of timekeeping architectures for both GPS and communication satellite systems **[6]**.

As an example of our applied physics work, Figure 1 shows the basic Advanced-EHF (AEHF) timekeeping system. In broad terms, the AEHF Satellite Mission Control Subsystem (ASMCS) maintains the AEHF timescale with a cesium (Cs) atomic clock that is synchronized and syntonized to Universal Coordinated Time as maintained by the United States Naval Observatory. Each satellite in the constellation is assigned a specific timekeeping role: Master – MSR, Monitor 1 – MON1, Monitor 2 – MON2, or Slave, and the timekeeping on each of these satellites is maintained with a rubidium (Rb) atomic clock **[7,8]**. Together, the MSR, MON1, and MON2 are referred to as the "Triplet," and this Triplet is present so that the constellation can autonomously evaluate its timekeeping health. The Slaves of course follow the Triplet. Periodically, the ASMCS makes two-way time-transfer measurements of the Triplet members' time-offsets from the ASMCS Cs clock, and with these data employs an estimation algorithm to determine the Triplet members' time <u>and</u> frequency offsets. If any one of the Triplet members' time-offsets exceeds a threshold value, corrections are generated for all Triplet members and the constellation's time and frequency are updated.

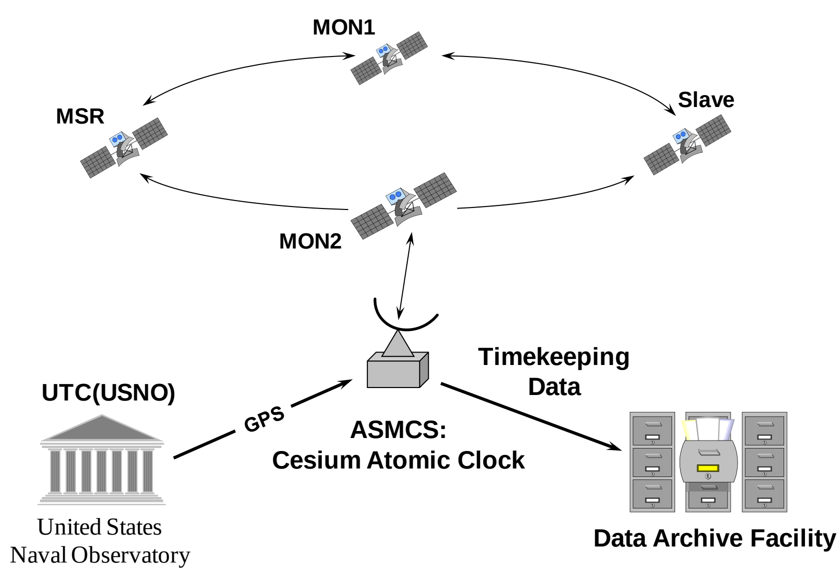

Figure 1. Cartoon diagram of Advanced-EHF timekeeping.

In order to evaluate the timekeeping algorithms employed by AEHF (e.g., the ground-station's estimation and control algorithms as well as the satellite slaving algorithm), we have built a Monte Carlo simulation of AEHF system timekeeping as illustrated in Figure 2 **[9]**. This simulation includes satellite and ground-station atomic clock frequency fluctuations, noise associated with the two-way time transfer process for both the uplink/downlink and satellite crosslinks, as well as temperature variations of the spacecraft clocks arising from the satellites' orbits. All of these time-varying realizations are numerically simulated and combined in order to generate a realization of spacecraft timekeeping. Running tens of thousands of these realizations, hundreds of years of timekeeping can be simulated, which then allows the construction of probability distributions for AEHF timekeeping. These probability distributions can be used to verify requirements and evaluate the timekeeping performance of the constellation under various operational scenarios.

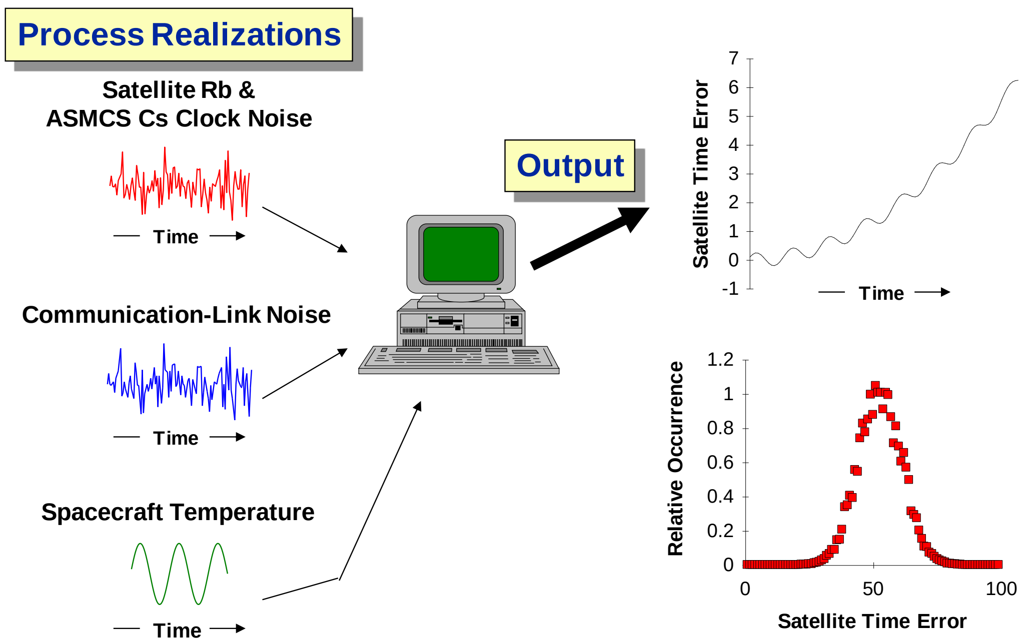

Figure 2. Block diagram of our Monte-Carlo simulation of Advanced-EHF timekeeping.

Figure 3 shows a single realization of timekeeping for AEHF with the *y*-axis in timekeeping units relative to threshold for a ground-station update. The effect of diurnal temperature variations is readily apparent, and for this figure the Slaving algorithm is chosen so that it follows an ensemble average of the Triplet members' time and frequency. Focusing attention on the 5th update interval, we can calculate a number of timekeeping statistics for the constellation: the mean time between ground-station updates, the worst time-offset of a satellite clock, and the time-offset of the slaves. Additionally, after the 5th update interval, we can simulate the constellation entering an autonomy period, and we can investigate the system's performance during such a period.

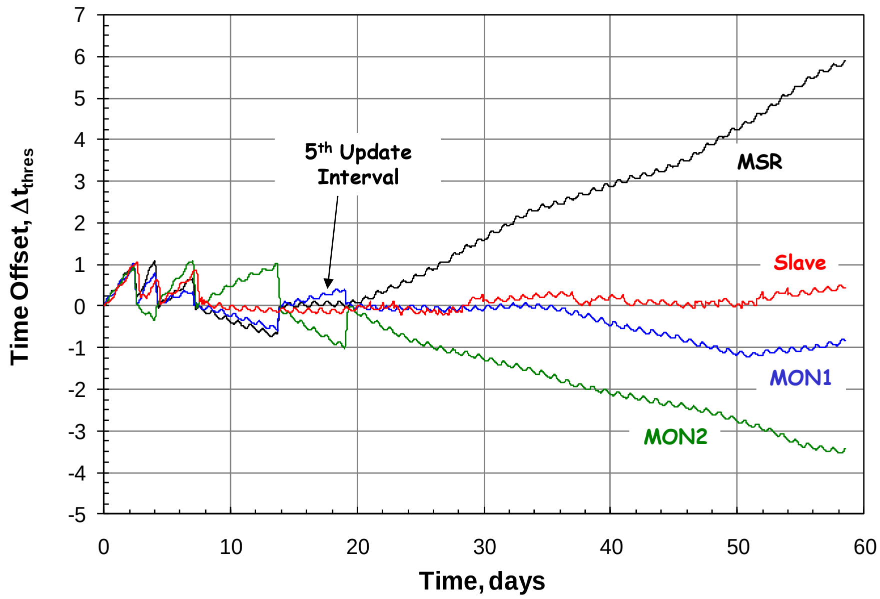

Figure 3. Illustrative Monte Carlo simulation of AEHF timekeeping as described in the text.

BASIC PHYSICS

In the area of basic physics, The Aerospace Corporation's precise timekeeping work focuses on the development of small, low-power, lightweight clocks for space applications. Many issues of basic physics associated with present-day and next-generation spacecraft clocks are often overlooked by the wider research community. In some cases, the basic physics questions of spacecraft clocks are not considered "hot" enough by academics, and so their interest in addressing these questions is not excited. Alternatively, manufacturer's often don't have the time or resources to focus on issues of basic physics. Nevertheless, if national-security space missions are to succeed and expand in their capabilities, these basic physics questions need to be addressed. At The Aerospace Corporation, we target our basic physics research towards problems that might otherwise fall through the cracks.

To help manufacturers develop next-generation atomic beam clocks for space, we have a research project looking into the development of a slow, continuous, cold-atom cesium beam clock **[10]**. Additionally, as rf-discharge lamps are a key component in the Rb clocks flown on GPS and milsatcom satellites, we are studying the operating characteristics of these devices to better understand how instability in their operation might arise **[11]**. We also have a project examining the general stochastic-field/atom interaction problem **[12]**, since laser noise properties in next-generation clocks may play an important role in limiting the devices' signal-to-noise ratios.

As an example of how basic physics that is not considered "hot" by the academic community may nonetheless be fascinating and of considerable importance for the improvement of spacecraft clocks, we have been studying the ring-mode to red-mode transition in alkali rf-discharge lamps over the past several years **[13]**. Briefly, as illustrated in Figure 4, at low lamp operating temperatures the Rb light emitted by the lamp comes from a ring around the lamp's face. In this "ring-mode," the amount of Rb light emitted by the lamp increases with temperature and so too does the Rb clock signal. At high lamp temperatures, however, things change: although the Rb emission still comes from a ring around the lamp's face, the lamp takes on a more uniform red appearance. In this "red-mode," the clock signal is found to be a decreasing function of lamp temperature. We have discovered that this ring-mode to red-mode transition is driven by radiation trapping: when radiation trapping is severe the ionization process of Rb allows for lower electron temperatures. As illustrated in Figure 5, this lowering of electron temperature results in a sharp decrease in noble gas (e.g., xenon line) emission, and a decreasing efficiency for optical pumping as Rb photons diffuse into the emission lineshape wings (i.e., the photons suffer multiple resonant scatterings on their exit from the lamp vapor). Quite recently, we discovered that in a very narrow band of temperature near the ring-mode to red-mode transition the lamp can enter a regime of self-sustained oscillations. We are presently performing experiments trying to unravel the mechanism giving rise to this self-pulsing behavior.

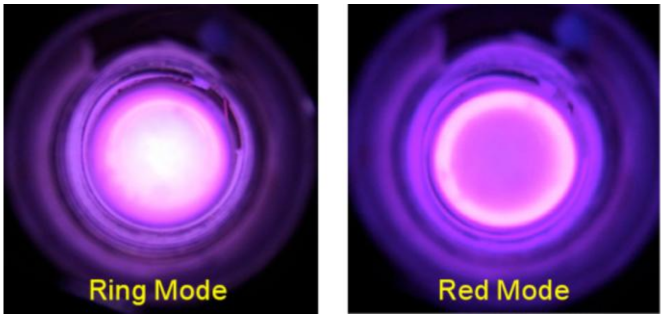

Figure 4. Pictures of the ring-mode and red-mode in a Rb rf-discharge lamp. On the left, the "ring" is defined by the reddish glow; on the right, the image has a more uniform reddish glow throughout the bulb.

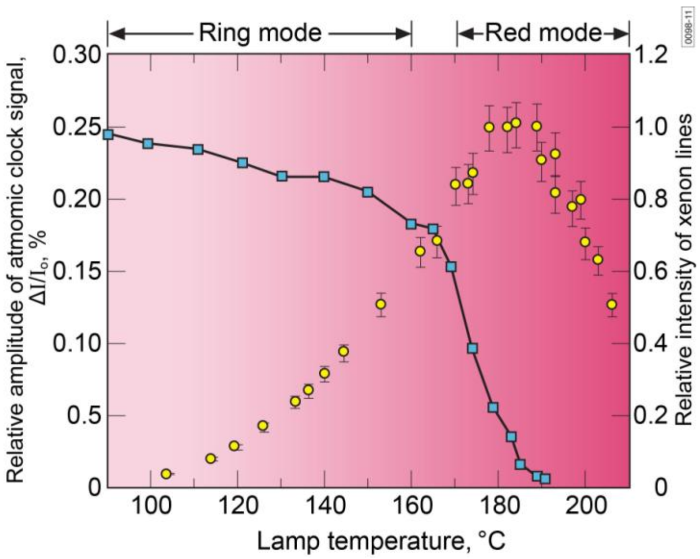

Figure 5. For a Rb/Xe rf-discharge lamp, this figure shows the relative intensity of xenon lines (blue circles) and the relative amplitude of the 0-0 clock signal (yellow circles) as a function of the lamp's temperature. Note that the lamp temperature scale may be off by ~ 20 ^{o}C, due to the well known difficulties in extracting Rb vapor temperatures from an operating discharge lamp.

As an additional example of our basic physics research, in order to better understand how lasers might give rise to new and unexpected noise sources in atomic clocks we have been examining the response of coherent-population-trapping (CPT) atomic clock signals to the presence of laser polarization variations **[14]**. We believe this may have relevance to chip-scale atomic clocks, where the laser of choice, the Vertical-Cavity Surface-Emitting Laser (VCSEL), is known to exhibit intrinsic polarization fluctuations **[15]**. In our latest work illustrated in Figure 6 **[16]**, we have discovered that under relatively rapid laser polarization modulation the CPT resonance can split into a doublet, and we are now beginning studies looking at this splitting when the laser polarization is stochastic (i.e., composed of a broad range of modulation frequencies).

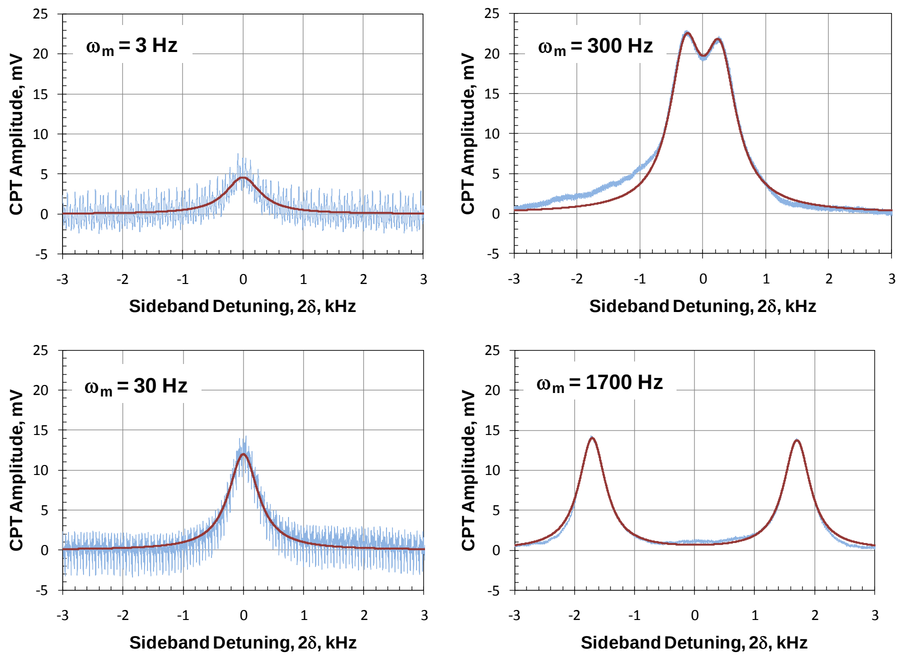

Figure 6. At low modulation frequencies we obtain the standard CPT resonance. At intermediate frequencies (i.e., 30 Hz) the CPT amplitude increases, since atoms don't have time to become trapped in a non-CPT participating atomic state. At the highest modulation frequencies our CPT resonance splits into a doublet.

SUMMARY

The Aerospace Corporation advises the U.S. Air Force and other government agencies on issues of national-security space, and to satisfy this mission the corporation maintains expertise in the full range of precise timekeeping endeavors: the statistical tools required for precise timekeeping analysis, the testing of system-level timekeeping algorithms, and the measurement of precise time intervals. Additionally, we consider ourselves experts in the electronics of present-day and next generation space-system clocks as well as the atomic physics of present-day and next generation space-system clocks. Perhaps the most salient distinguishing characteristic of The Aerospace Corporation's timekeeping activities is that our focus is on satellite-system timekeeping, where the spacecraft must employ lightweight, low-power, and small form-factor clocks.

ACKNOWLEDGEMENT

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