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A LOOK INTO THE CRYSTAL BALL, THE NEXT 25 YEARS

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Abstract

The PTTI Planning Meeting was born at about the same time as the atomic definition of the unit of time, the second. This use of the cesium resonance was made possible by advances in quantum electronics during the preceding decade which resulted in commercial availability of cesium, rubidium, and hydrogen clocks and frequency standards. Twenty–five years later these types of clocks still are the backbone of time and frequency applications; together with a variety of crystal oscillators, transmitters, and receivers, as well as signal distribution, conditioning and switching systems, atomic clocks are an essential part of the infrastructure of modern navigation and communication technology. The next 25 years undoubtedly will see a pervasive expansion of PTTI into the infrastructure that supports and leverages industrial, social, environmental, defense, and even individual human activities. Speculation as to what capabilities, services, and personal conveniences may become available, will be limited by two factors: the degree to which existing device concepts can be made more affordable and reliable, and the ability to miniaturize for purposes of compatibility with electronic integration. With regard to the latter, history teaches us that the required technological breakthrough is unlikely to originate in existing technology; thus, we may expect a paradigm shift in PTTI device concepts not unlike the shift in the 1960s from vacuum tubes to semiconductors.

Historical Perspective:

The PTTI Planning Meeting was born nearly coincidentally with the atomic definition of the unit of time, the second. This use of the cesium resonance was made possible by advances in quantum electronics during the preceding decade which resulted in commercial availability of cesium, rubidium, and hydrogen clocks and frequency standards. Twenty–five years later these types of clocks still are the backbone of time and frequency applications; together with a variety of crystal oscillators, transmitters, and receivers, as well as signal distribution, conditioning and switching systems, atomic clocks are an essential part of the infrastructure of modern navigation and communication technology. The underlying three driving forces that maintain and expand this infrastructure are performance, reliability and affordability of the products offered.

The currently deploying systems of globally networked time[1], satellite–based global navigation[2], and high data–rate global communication[3] via satellites, cable, and optical fiber are summarized in Table 1 under "present". Their demands are changing the balance of the three major driving forces that govern the development of hardware and systems: Affordability and reliability have become more important than performance, and, in most cases, either one of them is actually the dominant driving force. This should come as no surprise because time and frequency devices have graduated from laboratory applications and systems feasibility demonstrations to critical components in global networks that are essential to the functioning of modern, industrialized societies. As a further consequence, it has proven extremely difficult to introduce new products with unproven reliability and only marginal or no advantage in performance or affordability. The primary driver in networks is reliability. Once operational, the prime objective of any network is to remain operational and to never disappoint a (dependent) user. Reliability concerns may be motivated by national security, safety, business, or other factors.

Three subordinate elements of reliability are device related; i.e., they are attributes of the clock, oscillator, or receiver: MTBF, turn–on and environmental sensitivity. They can be modified by the technology used, by the design concept, and by detailed design, as well as through parts and materials, manufacturing processes, and storage and handling. The remaining three subordinate elements (redundancy, graceful degradation, and autonomy) are systems related: Redundancy can be achieved by device back–up with one or more spares and often sophisticated switchover that may have to preserve phase and/or frequency. Graceful degradation refers to a careful balance between network and device functions such that network signals can be used to interpolate or even mimic device functions should particular devices fail. Last, but not least, autonomy is a critical concept in networks allowing stand–alone operation of network subnodes, nodes, or subnetworks in case of breakdown of either devices or networks links. Local, regional or even global autonomy is the driving force for the deployment of precision clocks and oscillators within networks; a good example for this is the triple–redundant atomic clocks on board the GPS satellites.

For users, the primary driver is affordability. The user will seek alternatives to time/frequency based solutions if the required performance cannot be afforded. One must keep in mind that affordability is a relative term; e.g., the user will not acquire a clock, oscillator, receiver, or related subsystems if their acquisition or operational costs approach the cost of the host system or platform. Many years ago a proposal for an aircraft collision avoidance system floundered because the cost of a cesium clock exceeded that of some small aircraft!

Evolution of Clocks and Systems

Figure 1 depicts, in its upper part (1950 to 1990), the evolution of clocks and of the time and frequency infrastructure that support today's navigation, communication and dissemination[4, 5]. If we look further in the past, beyond 25 years, to the most significant predecessor systems, we find those depicted in Table 1 under "past". It must be noted that in the evolution of systems (Table 1), as well as in the evolution of clocks (Figure 1), substantive paradigm shifts took place: Fields of science and technology quite unrelated to the original systems and clocks became the progenitors of the new generation of clocks and systems. Globally networked time did not evolve from railroad technology, GPS is not rooted in astronomy, ISDN is not a result of perfecting telephone and radio, and atomic clocks were not conceived by astronomers nor mechanical engineers. Sextant users and pendulum clock makers of the past could not have predicted GPS and atomic clocks. Thus, we should expect another paradigm shift in the future: Although today's clocks, systems, and infrastructure will further mature and grow in scope as well as numbers, the developing intense demand for affordable, reliable, and usable devices will probably not be met by today's time and frequency technology. As in the past, scientific and engineering breakthroughs in unrelated fields will likely displace today's devices. Therefore, it may be of some use to elaborate on the promise of a few, selected technologies:

Important Technologies

a. Advanced ceramics are already of importance for essential components of time and frequency products such as cavities, resonators, and structural components. In addition, advanced ceramics are of great importance to dielectric's and dielectric substrates and thereby to all applications of electronics, especially at very high frequencies. Also, advanced ceramics can be designed to feature certain properties; thus, they offer the potential of engineered material characteristics as required by the designer of a product.
b. Microelectronics and optoelectronics, especially very large scale integration, are of enormous potential for miniaturization of time and frequency devices. Developmental circuit integration is now being pursued at feature dimensions of a tenths of a micrometers or less (quantum wells) offering complete integration of analog, digital and computer functions as well as optical interconnects on one small chip. Furthermore, optoelectronics is important for signal detection as well as signal transmission, especially with very low noise characteristics.
c. Physical and chemical manipulation at the nanometer scale has become possible through advances in lithography and microscopy (scanning, atomic force, etc.). This has led to a new technology, micro–electromechanical (MEM) device technology[6, 7] and to the ability for large scale integration of electronic, optical and even mechanical components.
d. Thin–layer technology is a pervasive generic technology for a great number of applications. These include surfaces of detectors, optical emitters, and crystals. Metalization of crystals, coatings of storage vessels, and gettering surfaces are but a few examples where a better understanding may lead to control of the interaction between solid and liquid, solid and gas, and solid and solid phases.
e. High temperature superconductors offer options ranging from low loss cavities and resonators to advanced high speed electronics and chip–size oscillators based on Josephson junctions [8]. Also, efficient magnetic shielding and shielding against electromagnetic interference as well as the exploration of nonlinear electromagnetic phenomena (mixing and multiplication) appear possible.

Based on the above, it is reasonable to predict extremely stable clocks and oscillators based on solid state or surface phenomena and/or on arrays of electronic, optical or quantum effect components, each of nanoscale dimensions. It is equally reasonable to predict extremely fast electro–optic switching as well as integrated networking with switches, amplifiers, clocks, phase shifters, transmission lines etc., at the nanoscale, mere components of an integrally fabricated system whose reliability and affordability is extremely high; at least as high as today's integrated electronic chips.

Conclusions

The next 25 years undoubtedly will see not only new devices and capabilities but also the pervasive expansion of precision time and time interval techniques into the infrastructure that supports and leverages industrial, social, environmental, defense, and even individual human activities. Reality, as to what capabilities, services, and personal conveniences may become available, will be limited by two factors: the degree to which device concepts can be made affordable and reliable, and the ability to miniaturize for purposes of compatibility with electronic integration. With regard to the latter, history teaches us that the required technological breakthrough is unlikely to originate in existing technology; thus, we may expect a paradigm shift in time and frequency device concepts not unlike the shift in the 1960's from vacuum tubes to semiconductors.

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TABLE 1 PAST AND PRESENT MAJOR SYSTEMS

- **TIME/FREQUENCY:**

  PRESENT:
  GLOBALLY NETWORKED TIME
  (10^{-14} SYNCHRONIZATION)

  PAST:
  RAILROAD SYSTEMS

- **NAVIGATION:**

  PRESENT:
  GPS, GLONASS (METER ACCURACY GLOBALLY)

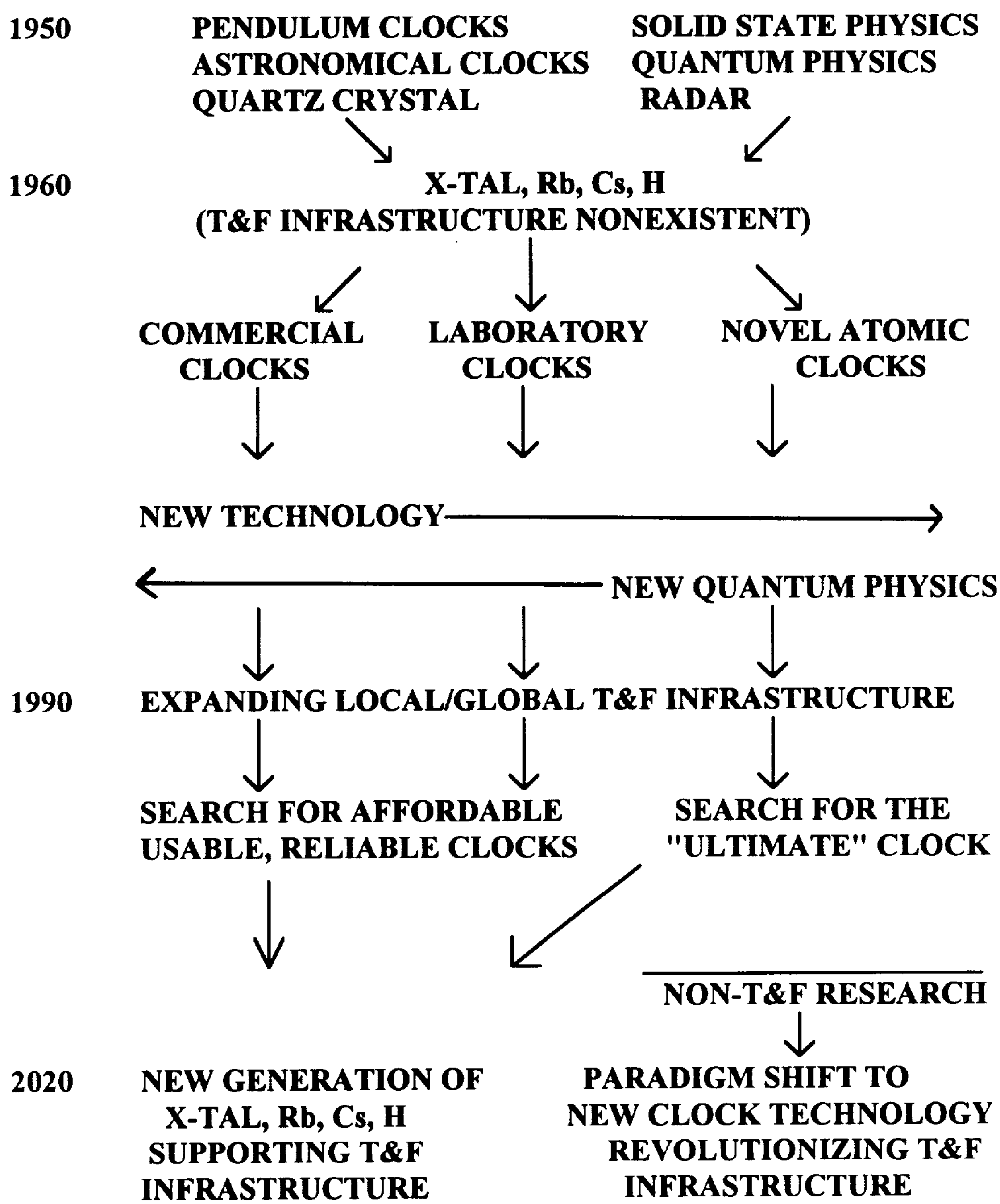
  PAST:
  STAR OBSERVATIONS (SEXTANT)

- **COMMUNICATION:**

  PRESENT:
  ISDN, SONET (GIGABIT GLOBAL NETWORKS)

  PAST:
  TELEPHONE AND RADIO (ANALOG/VOICE, MORSE, TELEX)

FIGURE 1 REVOLUTION OF CLOCKS AND INFRASTRUCTURE



QUESTIONS AND ANSWERS

Claudine Thomas, BIPM: I would just like to add one comment on something I am concerned about. I would say that I prefer that improvement in time and frequency may help communication between people rather than making war. Don't you think so?

Dr. Hellwig: I couldn't agree with you more. But if there has to be war and if there has to be a forceful dealing with bad things in this world, including terrorism, don't you agree that if you have to deal with that we will have a hard time as a world community to avoid, that it is better if we have an ability to just deal with that than with everything around it? Like blowing up the World Trade Center and things like that. I am realistic enough to say that we do need some military capability. I personally prefer military capabilities that do harm only to those who have to be harmed.

Dr. Winkler: Just a comment. In your initial draft, you showed a development of the new technology unbeknownst by the old one. I would say it was deliberately disregarded. It was not unknown. And we do the same thing today.

Dr. Hellwig: Yes, I think you have deeper insight into that. I grew up with the new technology, right. Yes, I think you were right. And you were in the middle of it back then. And that is why I am a little overly enthusiastic. But I agree with you. We are ignoring the other side now. Whether that is good or bad, I don't know. Because it would take place anyway, in my opinion.