IMPACT OF IMPROVED CLOCKS AND OSCILLATORS ON COMMUNICATIONS AND NAVIGATION SYSTEMS
(Special Report)

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In September of this year, the National Bureau of Standards held a Workshop in the Washington D.C. area which addressed the role of clocks and oscillators in large scale systems, particularly communications and navigation. The ultimate purpose of this Workshop was to do two things: first, to provide research and development people in government, at universities and in companies with adequate information to appropriately direct their research activities towards the real needs for clock and oscillator improvements; second, to determine whether or not there are any ways in which existing oscillators and clocks could serve systems better than they are doing now. The Workshop took place over a period of three-days, with several technical papers and two panel sessions which were instrumental in determining the state of opinion in this field. Many government agencies and private companies were represented. I am not going to repeat the technical details. Instead, I would like to present a distillation of the ideas and concepts; some of the ideas are my own, but many came from other participants.

There are two generic alternatives to obtaining timing information in a distributed system - the use of independent clocks or the use of coordination. This paper will not address this choice at all, but will concentrate on systems which use clocks. For military systems in particular and in many cases for civilian systems, there are reasons to choose solutions based on precise clocks or oscillators. Low error rate in digital communications, anti-jam characteristics and fast signal acquisition all require very precise timing information. Survivability and independence depend upon a priori knowledge that comes from having precision clocks in the system and that is not available to unauthorized persons. Independent operation of system elements protects the system from human error and various disasters. Finally, there is often fallout resulting from the inclusion of clocks and oscillators in a system. For example, having a very precise oscillator on a satellite permits improved determination of the orbit of that satellite. This technique is being applied today in the GPS system and may be applied in the future to many satellite systems if the satellites carry low cost but high precision clocks.

In a paper presented at the last PTTI conference, two basic mechanisms were suggested for achieving improved systems; better clocks and system redesign could lead to improved performance or different operational procedures and system redesign could lead to relaxed clock dependence. The conclusion which I reached as a result of the Workshop is that the real deficiency from which we suffer today is a lack of effective and efficient utilization of existing resources. Engineers today, particularly systems engineers, will often go a long long way to avoid using clocks in their systems. The JTIDS system is probably a good example of that. The operator needs to enter his time with approximately 6 second precision. Doing better does not save any time in acquiring utilization of the system. Typical requirements to satisfy the position location, identification and the information distribution aspects of the system can be accomplished with oscillator precisions in the 10^{-4} to the 10^{-7} range, orders of magnitude below what is available today. I am going to discuss why this situation occurs and then how to optimize the use of available devices to achieve the required performance and reliability and how the specification of oscillators affects our ability to accomplish this at minimum cost. We will consider the traps of applying false economic considerations and the problem of functional duplication where many subsystems provide the same attributes and none provide the reliability and the redundancy that is necessary. There was a near unanimous agreement that more development is needed on two fundamentally different varieties of clocks. We will review the state of the industry and its capability of providing these requirements.

There is a large gap between what is being produced and the state-of-the-art, i.e., what has been achieved in the laboratory under ideal conditions. One of the things that we'd like to be able to do, of course, is to purchase large numbers of these best units. The idea may be a little bit controversial but I believe there really is no large problem with regard to the ultimate performance capability, i.e., the noise floor of our existing technology; combinations of hydrogen, rubidium, and cesium standards have been demonstrated to provide pretty much all that most people need at the present time. However, there are significant areas of deficiency relating to operating standards in the field. The turn-on time, the environmental sensitivity and the radiation resistance of our current standards simply do not satisfy systems designers. Many systems, SEEK-TALK and JTIDS for example, would like to have oscillators with any where from a part in 10^{9} to a part in 10^{11} precision and accuracy that turn on in 30 seconds. Operationally, they are using oscillators that turn on in 40 minutes at the part in 10^{8} level. Commercial manufacturers have published results of oscillators that accomplish parts in 10^{10} repeatability in five minutes. So there is a large discrepancy. System functions are also pushed onto the clock with unenviable results. Manufacturers are asked to provide output at frequencies such as 5,10,10.23,5.115,9.116 and 4.016 MHz. They are also asked to provide high degrees of setability and tunability which are essentially system functions.

The first area that I would like to talk about is probably the most important one, reliability. It is something that we pay lip service to, something we worry about after the fact. One of the major concerns expressed in the Workshop was what can we do today to plan for reliability in our future developments? The performance which we need exists; the reliability that we want is only going to come from more experience with the very standards that we currently have. We make the mistake of constantly trying to push the state-of-the-art and push the performance of our standards with the same devices that are supposed to produce high reliability and a long lifetime. The only way we are going to find the problems in clocks and oscillators and solve them is to produce hundreds of these devices, and get them out into field operation so that the design flaws which are built-in can become known. Otherwise there will be a wide variety of circuits and features in supposedly high reliability devices that have only been produced two or three times. The strategy which I recommend is that we invest our money in buying large numbers of identical clocks. This will help generate a guaranteed market for the companies that produce the clocks and will encourage the needed engineering and development investment in the clocks. This approach would be costly, but not as costly as the failure of important systems. Another consideration that we should take into account is that the various attributes which we assign to a clock are not independent. For example, if we want super performance from a device then we are going to have to pay for that performance in a variety of areas, in reliability and cost for example.

The use of custom made devices is another significant problem area. We tend to set goals for our system clocks which are either the best results we know of or, worse, something a little bit better. We ask the small R&D company to develop a few units with that performance but also having custom features that match our system requirements - our frequency, size, configuration, power, weight, and warmup time. But custom units in general perform worse than standard off-the-shelf-units. Not only that, the process of producing a customized product ties up the technical capability of the small company which is then not available to do the advanced development needed to get better performance. This scenario is probably true even in the case of the most trivial changes because the risks of making these changes are high.

We do a further disservice by not paying enough attention to the whole problem of specification. The process of specification is unique to each system application and cannot be done in a generalized fashion. We should always use the ultimate criterion; if the system is to provide timing, then the specification should be in terms of the maximum time deviation permitted for the duration of the mission or experiment. Systematics are particularly important to specify correctly. Several kinds of modeling can be done, but most often, modeling is unsuccessful in removing systematics. The principle reason is that the systematic effects of the clocks often have the same functional dependences as the systematics from other parts of the system. The GPS program is a good example of that. Quadratic systematics in the clock are inseparable from similar phenomena in the orbit.

Our specifications are often unreasonable. We sometimes specify a much better device than is needed because we know it is producible, but that runs up the cost and prevents the manufacturer from trading off that performance against some other important criterion. One has an obligation to specify the true system performance requirements rather than anticipate unforseen eventualities. Once the specifications of a system are fixed, the performance of the system clock or oscillator is determined. A different system design might not require the same oscillator performance but once the requirements are set one is forced to pay for the unnecessarily difficult specifications. A related problem is the totally ingrained notion of many engineers that they know the value of the clock in their system _a priori_, based upon the final price of the system. I think this _a priori_ "knowledge" of the value of the clock is grossly in error. For example, quartz oscillators look rather simple. They are small devices; the best of them cost only a few thousand dollars. Systems engineers sometimes don't comprehend that the state-of-the-art quartz oscillator is splitting a resonance line to a part per million. This is mostly a science, but partially an art. It is not a situation where additional engineering effort is going to produce a fundamental decrease in the cost. As another example, I'd like to talk briefly about possibilities for a very inexpensive GPS receiver. The performance achieved in the GPS system is interesting for commercial applications. The clear acquisition signal has more power than the P code and it may become available on both the L_1 and L_2 frequencies. People are talking about two-printed-circuit-board receivers that will sell for $2,000 and cost less than $1,000 dollars to produce. In this context, the value assigned to the clocks is $150 and the performance requirement is a part in 10^{11} stability for hundreds of seconds. It is probably impossible to produce such a device with today's technology.

The development costs of custom clocks and oscillators are usually not recoverable by sales of a large number of units. In fact, the small, high technology companies that serve the custom product market run the risk of developing new devices which, if they have large profit potential, may attract other companies to compete for the market. In addition, specifying state-of-the-art performance in a system diminishes the possibility that there will be significant economies due to large scale production. Super high performance is achieved by a process of measurement, testing and selection and these processes are labor intensive. In fact, they are essentially an impediment to ever producing large numbers of super high performance clocks. We need to recognize that research and development for new products will have to be paid for by the government or by the systems developer.

In order to improve productivity, it would be beneficial to separate the problem of making a device that works from the problem of making it in a cost effective manner. The engineers and scientists who have to produce new developments should not have the added burden of doing it inexpensively. I have seen this policy applied in the solar power conversion industry and it appears to be very successful. We ought to increase the utilization of standard components in a variety of systems. One aircraft could eventually carry operational JTIDS, SEEK-TALK and GPS receivers. Right now, because of the differing specifications those will all contain independent frequency standards. There is no reason why they could not all run from a single distribution unit. In fact, there is an advantage because of the redundancy resulting from using an ensemble of standards.

There was a consensus of opinion at the Workshop that there are three types of standards requiring more development. The first is a special purpose standard. Various systems stress different attributes which can be combined in a single device. The JTIDS system needs fast warmup. A part in 10^9 accuracy satisfies all functions of that system. The SEEK-TALK program is princpally interested in achieving a part in 10^{10} accuracy with fast warmup. For GPS user equipment, stability is important in commercial applications which observe satellites sequentially. Spread spectrum communication systems need near zero bit error rates which requires in the vicinity of part of 10^{10} to parts in 10^{11} stability. The second type of standard needing further development is the very, very high stability oscillator. Parts in 10^{14} and better performance have been achieved, but the devices are not field deployable and are not sufficiently reliable. This kind of performance is needed for times up to a week in order to increase calibration intervals, to speed up measurements, to allow the use of higher frequencies in our communications systems, and to make better use of station keeping satellites in TDMA systems.

What is the state of research and development that is supposed to produce these results? Crystals, cesium, rubidium and hydrogen are all old technologies. We are existing off the developments of the past, but there are many new ideas. In fact there is a plethora of new ideas, only a few of which may be superior to the existing concepts. We must carefully analyze this situation, and put our research and development resources in the direction of devices that really have potential for replacing or adding to the existing concepts. Advanced development is in a worse state. Whereas, the civilian and the military funding agencies spend a fairly large amount of money on basic research, there is not much funding for advanced development. Private companies are tied up producing the customized devices required by systems engineers. Bell Telephone which was spending millions per year on crystal research is now out of the field, having satisfied their own needs for the foreseeable future. Organizations like the USAERADCOM are shrinking in size, no longer providing the advanced development that they were doing at the end of the second world war. This problem is exacerbated by the fact that the development of the standard up to the preproduction model is far more costly than the initial laboratory demonstration. Even if the new clocks and oscillators needed by our systems in the near future are developed we will not easily be able to manufacture them. The manufacturing capability that is needed is considerable. The utility type standards will be required in quantities greater than ten thousand units, and they can't be created overnight. It will probably take years and cost millions of dollars to establish that kind of production facility. We've even lost some of the facilities that we had. Our crystal capabilities have gone overseas for the most part; the entire commercial industry to Japan and 50% of the precision capability is gone. There is only one source of precision crystals in this country marketing resonators without oscillators and the quality of the quartz that is available has deteriorated markedly since 1970.

Finally, there is also a problem of system implementation. We all share this problem; we get caught up in developing new things. That's where most of the credit lies. We are so caught up in developing new things that good devices already developed are often not implemented. The new technologies never get to mature. On the other hand, technologies that are out in the field aren't replaced. Some are 40 years old and they are not only mature they are senile! It is necessary to separate the problems of research and production. We have to be satisfied with using devices that perform well, even if next year's device will perform better. We have to get those devices out into systems and we have to concentrate on the research and development that will produce new devices for the future. Systems engineers should worry about systems problems. It will continue to debilitate clock research efforts to continue considering things like output frequency, power level, tunability and other system attributes to be problems for the clock designer to solve.

QUESTIONS AND ANSWERS

DR. WINKLER:

Thank you very much, Sam, for your very thoughtful remarks. Maybe a little pessimistic, but it is certainly better to face the issues and I wonder whether we have any comments to that?

MR. VESSOT, Smithsonian Astrophysical Observatory

I think one thing that has been perhaps overlooked is that the technology that has led us to the successes we have made, have rarely come from an intention to develop a clock. If you look in the past, I suspect that the pendulum had nothing to do with the clock when its properties were first observed, and going a little more recently, the discovery of Cate's electricity had nothing to do with crystal oscillators. Ramsey, I am sure, didn't design his Ramsey Structure with the idea of making a clock. He was out to resolve some spectral lines. And the masers and lasers, I am sure, weren't motivated by clocks.

I guess what I am saying is that you can pour an awful lot of effort into directed research and get nowhere and I think what the country is lacking is the general outlook of undirected research in the hopes that technology can ensue that will benefit somewhere; but I really feel very uncomfortable about the attitude of, "Let's go and direct our fundamental research in a given direction". Applications nearly always arise from availability of technology, but requirements or needs don't always result in improved technology. And I think the main plea we might make is to hope that our support for fundamental research in the country will not be throttled back, and it is usually the first thing that is throttled back in a situation of a tight economy.

DR. STEIN:

I think you raised an extremely important point, Bob, and I didn't mean to imply that that wasn't true. I think it is very true. However, I was trying to elucidate some of the problems we have in accomplishing the transition from once you have identified a new technique, a new physical process, whatever it is, to then the implementation of a working clock, something like ion storage, cooled ions, lasers, are identified. They can be thought out very carefully. In many cases they are not thought out very carefully and we can identify, I think, where to best place development dollars.

DR. MCCOUBREY:

I agree with the remarks that Bob Vessot said, drawing attention to the declining support for the research that underlies these technologies that are important. I think there is another consideration also, which seems to me to apply in the case of the clocks, which have been important system components for many many years. I think that there has been less planning and less support for the design qualification and advanced development. I think you had your finger on it, Sam, when you pointed out the cost of advanced development to bring these things to a point of usefulness. It seems to me, for example, that in the case of other system components, for example, power plants and propulsion systems, or control systems, flight control systems, that there is a much greater amount of planning given to the refinement of the system and the qualification of the system beyond the development of the fundamental concepts in order to get components that are reliable. And I think one only has to look at the propulsion systems that are available and even the flight control systems now. Probably there are other components also.

DR WINKLER:

It is my impression that what is really at the root of what we are discussing here are two components. Number one, we have to ask ourselves well what are all these people doing now, which we would like to see working on the things which Sam Stein has mentioned, what are they doing? Well, they are gone? No. They are certainly still doing something and I think we may be overlooking the tremendous impact which we still have to see, which we still can, in fact, can expect coming from LSI technologies, from microcomputers, digital electronics, in other words. That impact has not yet come in the field of, certainly, of high precision frequency control. But it will; and it will change the scene radically, I think.

And number two, I think we are suffering, in fact, not from a syndrome of undermanagement or mismanagement but from overmanagement. It is a question of-- Well, I see a great deal of sympathy in the audience to what I say and I feel very strongly about it, that if we would devote all these energies which are being spent today in trying to split up things exactly into certain bins, 6.1, .2, .3, .4, .5, and to decide exactly what should be done and what should be done here. We are overdoing things. That is really what Bob Vessot has meant, that we cannot specify in such detail the future. It is impossible. We have to allow a certain degree of freedom, of liberty. If we do away with it, if we become completely enslaved to superplanning I think we will be in serious trouble in these advanced R&D concepts. There have