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27th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting

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PTTI OPENING ADDRESS

Captain Kent Foster
Superintendent
U.S. Naval Observatory
Washington, D.C. 20392

Good morning, ladies and gentlemen, and on behalf of the U.S. Naval Observatory, welcome to the 27th Annual PTTI meeting.

Before I get started on remarks, I feel I'd be remiss if I didn't mention a few people's names who have done a lot of behind-the-scenes work to provide these facilities and services this week. You all may be used to this kind of service, but this being my first time here at a PTTI meeting, I'm really impressed. I did press Sheila Faulkner to give me some names of some people who have done some of the behind-the-scenes work, and I'd like to recognize them this morning.

In the area of general assistance, folks from JPL, Dick Sydnor and Paul Kuhnle; from AlliedSignal, Clark Wardrip; from Hewlett-Packard, Len Cutler; from Timing Solutions, Sam Stein; and from TrueTime, Don Mitchell. A special thanks to Sheila Faulkner herself and Nikki Jardine for all the hours of work they put in for the registration and the overall coordination. Very, very nice job, folks.

To many of you, I'm sure this a longstanding recurring event in your lives. To me, it's a first, as I assumed command of the Naval Observatory just this past August. As is my style when dealing with anything new and unfamiliar to me, I will do a lot more listening than talking at this event. When I do talk, I'm sure I'm going to be asking a lot more questions than providing answers.

I did manage to recover some history at the Observatory while preparing to make these remarks this morning. I went back 25 years to the Second Annual PTTI meeting held at NRL in Washington in December of 1970. I looked at the objectives laid out for the 1970 meeting and compared those to this session (see Figure 1).

The 1970 objectives can be summarized as: Disseminating information about PTTI; reviewing present and future requirements for PTTI; and reviewing current and planned PTTI systems.

The objectives for this meeting are very similar: The first, second, and fourth objectives are essentially repeat items of the 1970 objectives. One additional item was thrown in, that is, to inform government officials of PTTI technology and its problems. This new item seems very closely associated with the fourth objective, and I therefore think I can say that the objectives of this meeting are essentially the same as they were at the meeting in 1970.

Without checking the records of every meeting between 1970 and now, I think it's fairly safe to assume that each year's objectives were similar to the ones listed here; and if they weren't, they probably should have been. So after 25 years of aiming at the same objectives, where are we today?

When I look through the agenda of sessions one through ten of this meeting, they suggest the following to me: One, we are providing a lot of PTTI information to all attendees; and two, we are exchanging a lot of science and technology tied to PTTI. I think we could all feel confident about accomplishing objectives one, three and four here, based on the suggestions of this agenda; and I'm sure when this meeting adjourns, we will have our confidence verified.

What I don't feel confident about, however, is that objective number two, reviewing PTTI requirements, may not be getting a fair shake. I don't even see the word "requirements" in a single title in this agenda. I find this apparent inattention to requirements a little bit disturbing, and it's not the first time that I have found an absence of information–specific information–on this subject.

I know that I'm on a very steep learning curve in this new job of mine, and I know that I've got a long climb ahead of me before it even begins to level off. But the first easy lesson I learned is this: When you talk about current and future capabilities for precision accuracy involving time and positioning, especially those under development, the first question you get is "What is the requirement?" I've gotten the same question put to me by warfare-experienced Navy bean-counters–budgeteers–and laymen as well. When I turn to my prestigious ranks of PTTI experts at USNO for the requirements, especially the future requirements, I get a lot of looks of nervous uncertainty and a variety of very softly spoken numbers.

Figure 2 has been used in the past in USNO program briefs to show the long-term increases in USNO technology versus the increases in user requirements for precise time. I can tell you that the requirements line here is a rough quantitative estimate due to the uncertainty of precisely defined system-specific requirements. If, however, the slopes and the trends of this figure are generally correct, you can draw some inferences about the capabilities versus requirements.

From 1950 to about 1980, USNO technology preceded future requirements at any level of accuracy out to about 10 years. I guess this is probably a fairly comfortable margin. After about 1980, however, the technology development margin over future requirements shows a decreasing trend, as the lines beyond that point tend to converge. And by 1990, the relatively stable historical margin of USNO capabilities over current requirements begins to dwindle also.

These decreasing margins of capability over requirements should concern everyone here today. What this figure does not show is that the slope of the USNO capabilities line, which is of course the rate at which we can develop higher technology, is a partial function of resources, money, and people. Money and people are what all Navy and DoD activities are having to fight for on a continuing basis in order to minimize their losses. DoD is not a growth industry, and USNO is no exception to that rule.

USNO and other precise time activities do not launch combat aircraft; we do not put ships to sea; we do not aim and pull the trigger on any weapons system. We, therefore, in the eyes of war-fighters and defense bean-counters, don't do anything glamorous. But we do support marine and air navigation; we do support precise geo-location and putting weapons on target; and we do support synchronization of command, control, and communication systems. It's unfortunate, however, that these technical support functions are not well understood by war-fighters and bean-counters. The resources that provide these functions come under constant risk in competition with other more glamorous and high-priority requirements.

Our surest way to defend those resources against budget reduction drills, which are sure to continue, is through well-documented system-specific requirements, defined as precisely as possible and made understandable and appreciated by warfare commanders and bean-counters alike. This will not happen without the proactive involvement of the PTTI expertise assembled in this room.

I would like to repeat that for emphasis. Systems-specific requirements defined as precisely as possible and made understandable and appreciated by warfare commanders and bean-counters will not happen without the proactive involvement of the people in this room.

So I urge all of you to begin thinking and focusing on the requirements review that has been, I think, an objective of this annual meeting for 25 years, and of the process used by the Defense Department in validating requirements. We need to come to grips with better requirements definition and to be a part of the continuing requirements process. This is especially true for future requirements that we must have to support continuing technology development.

Well, having overshot my precise time interval assigned to me by this agenda, I'll turn this podium over to someone who needs no introduction for any prior attendees at these meetings. Dr. Gernot Winkler, of course, was Director of Time at the Naval Observatory for 29 years, and culminated his enviable career with retirement earlier this year. I'm thankful, though, that we still see and welcome Dr. Winkler at USNO a day or two a week, and I'm happy to say that he's here with us now to present the Distinguished PTTI Service Award.

Ladies and gentlemen, I thank you for your efforts and your interest here this week. Please now welcome Dr. Winkler. Thank you.

USNO

PTTI - Objectives

1970

1) Disseminate information associated with PTTI dissemination

2) Review present & future requirements for PTTI dissemination

3) Review status of current and planned systems for PTTI dissemination

1995

1) Disseminate and coordinate PTTI information at the user level

2) Review present & future PTTI requirements

3) Inform government engineers, techs and managers of PTTI technology and its problems

4) Provide an active exchange of new technology associated with PTTI

Figure 1

USNO

PTTI - Requirements & Capabilities

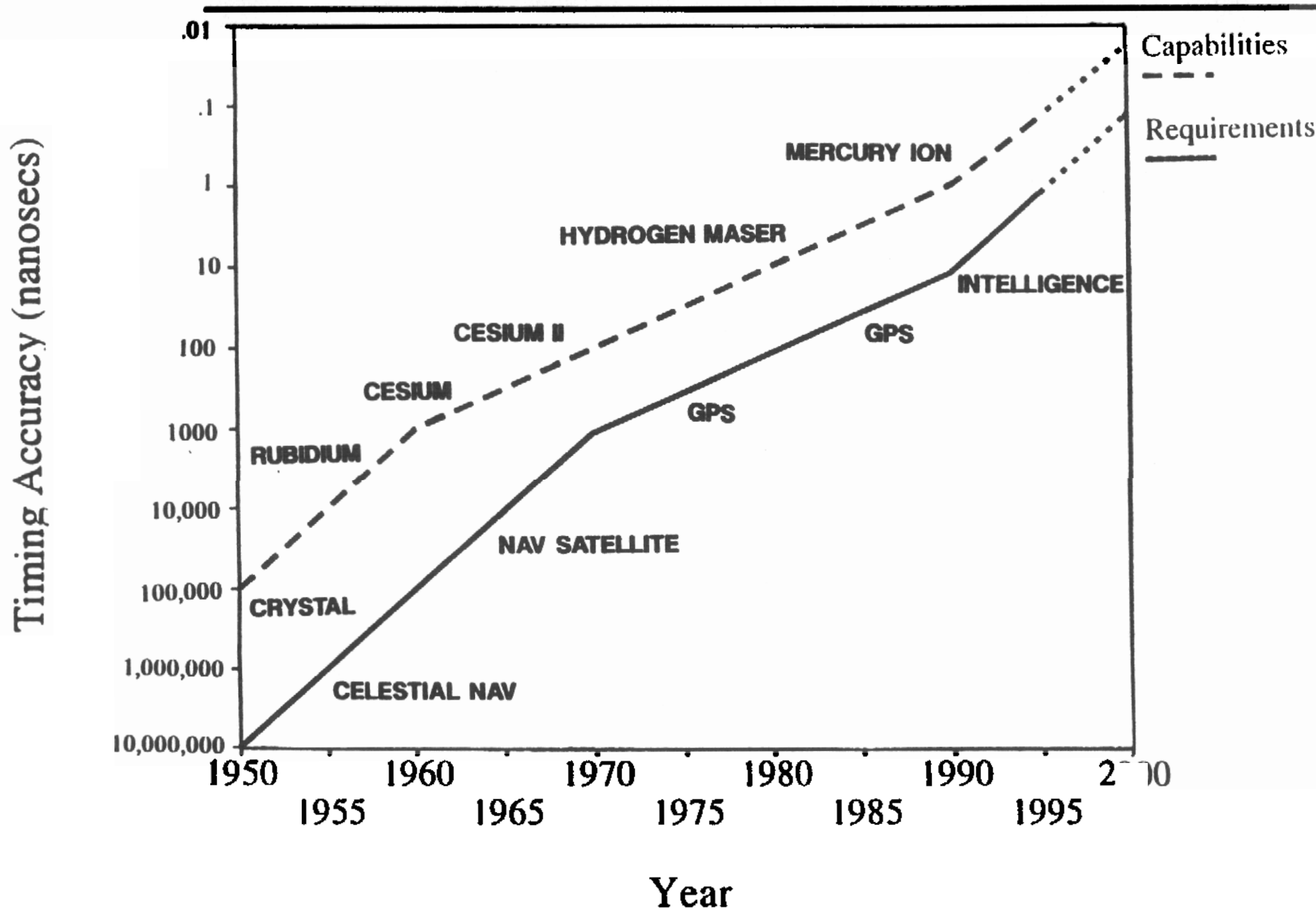
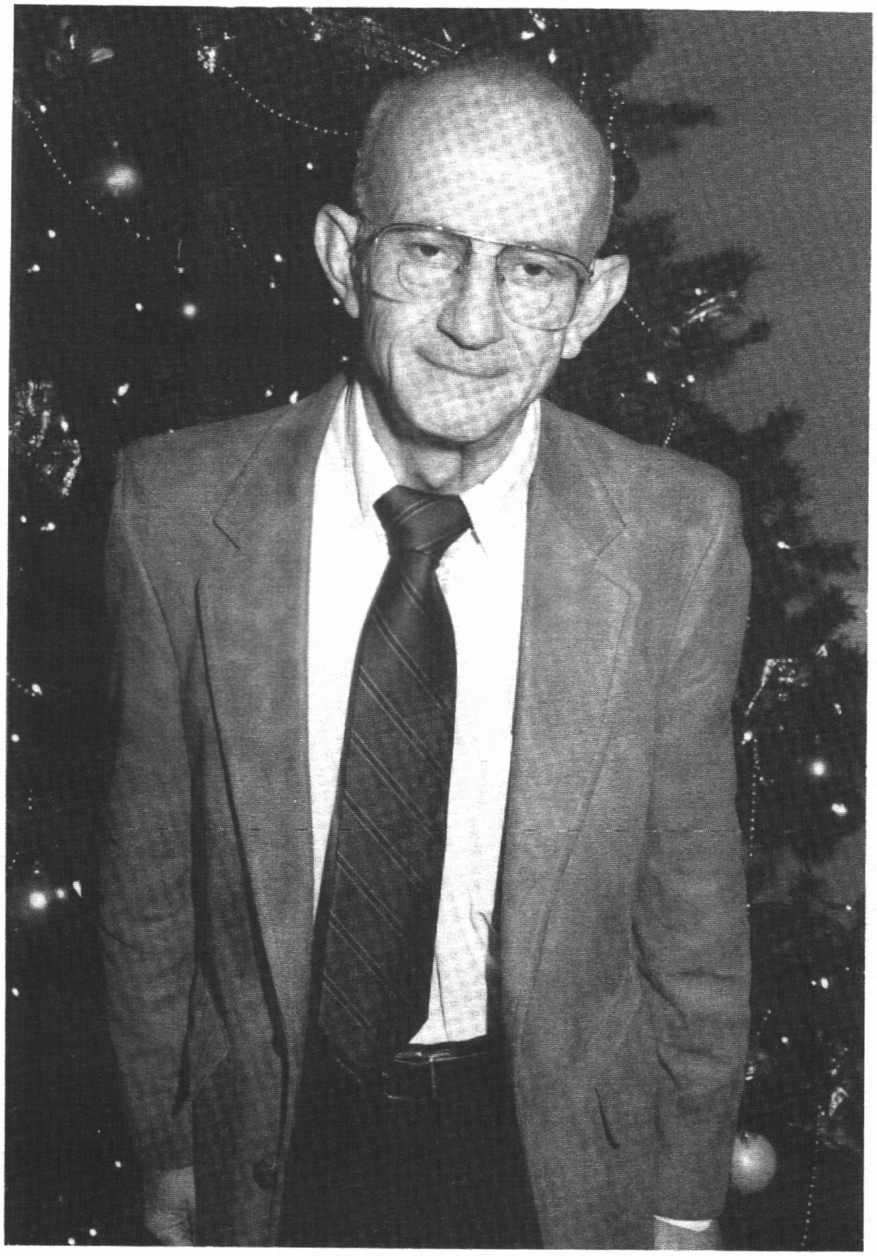


Figure 2



James A. Barnes

PTTI DISTINGUISHED SERVICE AWARD

Presented by
Dr. Gernot Winkler
USNO, Retired

to

Dr. James A. Barnes
Austron, Inc., Retired

Thank you very much, Captain. It is a very great pleasure for me to satisfy one requirement right here, and that is to recognize past achievements. I'm extremely happy that I can do that for my friend Jim Barnes, whom I have known for a long time, about 30 years. There is one thing which comes to mind immediately: his high personal qualifications, about which everyone agrees.

Jim's fairness has been recognized by quite a few people. And I want to read to you some of the comments which have been collected by David Allan, who wrote up the award citation. He has been an outstanding public administrator, bringing fairness and good will to his job. As the Time and Frequency Division Chief at the National Bureau of Standards (now NIST), he always treated outside agencies with respect and dignity. Dr. Cutler has added: "Jim has demonstrated both great depth and breadth in his solutions to problems. He is also a fine human being and an excellent leader. It is a real privilege to have known him for more than 30 years." These are the kinds of comments which have been made from old colleagues.

We owe him an enormous debt for his vision and follow-through in understanding and characterizing the random behavior of precision clocks. The tone of our whole community was set starting with his Doctor's thesis work in 1964 through his chairing the IEEE committee work leading to the classic publication in IEEE Transactions on Instrumentation Measurements entitled "Characterization of Frequency Stability," which has become a classic. The committee worked long and hard under his leadership to publish this pioneering work. In regard to this, Bob Vessot said "Jim's leadership helped pull together a coherent view by providing simple and elegant models to characterize the noise processes observed in clocks and oscillators."

Jim was born in Denver, Colorado. He will celebrate his birthday a week from this Thursday, at which time he will be 62. He received his BS from the University of Colorado, his Masters from Stanford, and his PhD back at the University of Colorado. He began summer work at NBS in 1956 with the Radio Broadcast Services Section, and the following summer worked with the Atomic Frequency and Time Interval Standards Section. In 1958, he joined NBS full time, and in 1965 he was appointed Section Chief.

A long list of awards and recognitions have come to him over the years, which we will not highlight here, as we wish to focus on his service. His pride and joy, however, are his children Lisa, Leslie, and Jimmy, and his grandchildren.

Though his contribution to the understanding of statistical models for precision clocks and oscillators is monumental, he has made very important contributions in other areas as well. David Allan has printed out five pages of just the titles and authors of his publications while he was at NBS.

In his earlier career, he did some very important work in precision spectrum analysis of microwave signals. And among other things, he also was one of the two people who transported physically the time from the old Greenbelt WWV station to Boulder, Colorado.

In 1964, the IEEE and NASA sponsored a symposium on the definition and measurement of short-term frequency stability. Looking back with 20/20 hindsight, Jim's presentation at this conference probably had more long-term impact than any other, and was the beginnings of much of what we accept as standards for measurement in our field. Dr. Golay, during a panel discussion, had great vision, as he commented: "I would like to congratulate Mr. Barnes for having come with an extremely logical measure of instability."

Some very important clarification work was added by Bob Vessot, and Bob's paper and a classic overview paper by Dr. Cutler and Campbell Searle of MIT were published along with the above two theses in the special issue of the "Proceedings of the IEEE" in February of 1966, a classic today.

September of 1967 marked the birth of the Time and Frequency Division of NBS, with Dr. Barnes as its first chief. Roger Beehler said of this era: "It was very important in the Bureau to have a good beginning for this new division. Jim gave it the leadership, pulled together a very good staff, and launched (very successfully) the work of this important division." We are all the beneficiaries of Jim's fathering this division's efforts.

Because of his recognized stature in our field, he was asked in 1980 to write the section in the Encyclopedia of Physics on "Clocks, Atomic and Molecular." He represented NBS for many years on the Consultative Committee for the Definition of the Second, and he has helped to steer international time and frequency activities in a healthy direction.

His work now spans over nearly four decades. And it is now with great pleasure that we give Jim his award as we express to him our deep appreciation for his outstanding service and contributions to our community. Jim, may I ask you to come up here?

As we all know, the fitting token of this award is, of course, a clock. What else? This is what we would like to present to you. It's a PTTI clock, not keeping time as well as the clocks at the NBS or NIST, or the Naval Observatory, of course, but at least something which you may find as a remembrance to the service to our community. Congratulations!

DR. JAMES BARNES: I would like to make two very brief comments. One is that I'm deeply honored by the award and I'm very pleased. I couldn't be more pleased with the chairman who just spoke to you. He was the first recipient of this award I understand. And I couldn't share it with better company.

One last thing is I've had some speech people help me at certain times. And they told me an interesting thing: If you have a lot of trouble, you say it very loud. And what I have to say then is **THANK YOU VERY MUCH!**

KEYNOTE ADDRESS PROGRESS OF TIMING IN TELECOMMUNICATIONS*

Ron Brown
Bellcore
Morristown, New Jersey 07960

Abstract

This talk provides an overview of why time and frequency are important in telecommunication networks. A historical perspective of the progress made in the telecommunication industry of both understanding and using PTTI are given. Switching, fiber-optic transmission, and wireless transmission are discussed. Finally, some prognostications about the future of PTTI in telecommunications are given.

It is a pleasure to be with you today, particularly in San Diego with the beautiful weather. I spoke to my wife this morning, and back in New Jersey they got an inch of snow. She was not too happy about having to shovel it herself; I am happy to be out here.

I am going to be talking about the progress of timing in telecommunications. The punchline of my talk is that the telecommunications industry has come a long way in the field of synchronization over the past 10 years, but we still have a ways to go.

Let me give a little background of who I am; I work for Bellcore. Bellcore is a software and consulting firm that is owned by the seven baby bells, and we do most of our business with the seven baby bells. I am chairman of T1X1.3, which is the standards committee that sets standards for synchronization for telecommunication systems.

One example of how far we have come in telecommunications, goes back to when I began working at Bellcore seven years ago. When I hired in, my boss at that time was Joe Ohweiler. During my first week on the job he said "Right now there's only one person who really understands timing in telecommunications. His name is George Zampetti, he works at AT&T, and I want you to find out what he's talking about, if it makes sense, and if he's trying to somehow put one over on us." That was my mission. In the past seven years, I've had a chance to learn a tremendous amount from a lot of different people. In the telecommunications industry today, we have a lot more than one person who understands timing. We have come a long way.

*Editor's note: This is a transcript of the oral presentation. Both the editor and the presenter have edited this paper.

One thing I want to say before I jump into my talk is Bellcore basically was created by lawyers and we have a lot of lawyers in our company. At Bellcore, it is very important for us to be unbiased. I'm going to talk about some specific companies in this talk. When I mention the companies, it is not an endorsement. In particular, I look at three companies that have really done a lot to drive progress in timing in the telecommunications industry. One of them is Bellcore, of course. The second one is AT&T Communications. The third one is Telecom Solutions, who builds timing equipment. So just because I mention those companies doesn't mean that I'm endorsing AT&T over MCI and Sprint or Telcom Solutions over HP, Austron, and all the other competitors in that field. I'm recognizing that they happen to have done a lot. I'm going to be around for pretty much the whole PTTI. If you want to get me off-line and ask about anything I bring up that we don't have time for questions and answers for, if you want to get in contact with me after the conference, my e-mail address is sync2@cc.bellcore.com.

What I'm going to talk about is why do we bother to synchronize telecommunication systems. As I was going through this talk, it was a little bit long, so I'm going to go over this very briefly. Next, I'm going to talk about general milestones that have happened over the past 20 years in telecommunications; and then look at some specific topics that I think are of particular interest to this audience. Finally, I will take a quick look at the future.

Why do we bother to synchronize telecommunication networks? At a very general level (slide 3), it comes down to two things: delay and bandwidth efficiency. A synchronized system can have lower delay because you can have smaller buffers. A synchronized system will have better bandwidth efficiency for several reasons. One example is that you don't have to waste bandwidth on frequency difference accommodation. Another example is frequency reuse schemes in cellular systems. Every now and then you'll read that bandwidth, because of fiber optics, is free. This statement drives me crazy. Bandwidth is never free. There are always trade-offs. What we have found that the cost of synchronizing the system has benefits that outweigh the costs as far as bandwidth efficiency.

This leads us to design systems to be synchronous. When there are synchronization faults, they can lead to data errors that are usually related to buffers overflowing or underflowing. Those are sometimes called "slips." There are also impairments called "jitter" and "wander". All of these are impairments, but they're second-order effects due to the general things that I mentioned before of controlling delay and optimizing bandwidth efficiency.

Another area that I'm not going to talk about too much, because it's not my main area of expertise, is cellular or personal communication systems (slide 5). When I look to the future, I think cellular, as they move from the analog systems to the digital systems, is a big area of growth for synchronization.

Let me give you some rough numbers (slide 8). I think this is mostly a scientific and engineering audience, but for those who might have a marketing interest, I want to give you an idea of the market size. The baby bells, who are Bellcore's clients, sometimes called "local exchange carriers," (LECs) have roughly about 1,000 switching offices each. Each one of these offices has a clock. There are seven companies that are true baby bells that were formed when AT&T was broken up, and then there are many other independent LECs as well. GTE is the biggest, and is actually bigger than any of the baby bells. There are a handful of smaller players, Rochester

Tel for example. All together, I'd estimate that LECs in the U.S. have about 10,000 switching offices.

Inter-exchange carriers (IXCs) are companies that provide "long distance" service, like AT&T Communications, Sprint, and MCI. They have larger networks in terms of geography, but much smaller networks in terms of the number of offices, anywhere from 10's up to about 100 offices. They also have some large offices that don't have switches in them. Because of these network architecture differences, they tend to treat synchronization a little bit differently.

End users have their own networks with their own synchronization needs. I am not able to put a number on this, because there are a lot of private networks out there that vary all over the map in terms of size. For example, if you look at a company like General Motors, they have their own network for hooking their manufacturing operations and their dealer network together. Almost every large company has some form of private network. Some of them take synchronization from their carrier, and some of them have their own synchronization sources.

Cellular is an area that I've identified as a high growth area for synchronization needs. Another is the international market. North America has tended to be a little bit ahead of the international market in the synchronization area. I think in the near future carriers outside the US will be starting to catch up and doing a lot more in the synchronization area.

Let me jump into the milestones, starting with the 1970's (slide 9). I was very young in the 1970's, I was eight years old in 1972. So I certainly don't remember this, but I've been told that that's when the first triplicated cesium ensemble was built by AT&T to time the analog network. But things were happening in digital systems in the 1970's as well. First of all, in the early 1970's – I think that really might have been the late 1960's – digital transmission technology was developed, specifically the T-1 carrier system. It was a way of digitizing voice and carrying 24 voice channels within one circuit. In the late 1970's, digital switching was developed. Digital transmission has very clear benefits as far as signal-to-noise ratio; you can transmit data long distances and maintain your signal-to-noise ratio. I think most people understand the benefits of digital transmission. The benefits of digital switching are a little bit less clear and it took a little bit longer to gain acceptance. Digital switches were introduced in the late 1970's, but it didn't really grow until the mid-1980's. The main benefits have to do with the fact that if all your transmission facilities are digital, then it's easier to hook those digital transmission facilities together with a digital switch so that you don't have to convert back to analog. When the digital switches interconnected the digital transmission facilities synchronization became critical. In a simple point-to-point network, synchronization is not that important. It's when you're switching time slots that are created at Point A at Point B so that you can get to Point C that those time slots have to be of the same size and network synchronization is important.

Next we move into the 1980's (slide 10). The BITS concept was introduced in the early 1980's. The BITS concept stands for Building Integrated Timing Supply and simply states that you should have one master timing source in each office. When the BITS concept was first introduced, the master clock was usually the clock in the switch in the office. Switches were large and cost on the order of millions of dollars. They had pretty good oscillators in them, so it seemed to make sense to use that clock to time the rest of the office. It turned out not to work that well because the switch's main purpose in life was to switch telephone calls, and it was not to be a synchronization box.

To address the shortcomings of the digital switch as a master synchronization source, Bellcore introduced the "True BITS" concept in 1986. The True BITS concept is differentiated from the BITS concept in that the master, or BITS, clock is a stand-alone clock rather than a clock embedded in a digital switch. Requirements for a dedicated, stand-alone synchronization system called a "Timing Signal Generator (TSG)" were published in a document called TA-378. The development of TSGs was important because now we had one box whose sole function in life was synchronization. By putting that emphasis on synchronization, we were really able to improve the quality of synchronization throughout the network.

1984 was the year of divestiture. Divestiture was a political event that drove of a lot of technical innovations that happened later. In 1985, Pac Bell deployed their own cesium PRS's – I'm going to talk about PRS's as their own topic a little bit later.

In 1986, a rubidium Stratum 2 clock was developed. In telecommunications, we have a hierarchy of clocks. The T1.101 synchronization standard defines four strata in the hierarchy. Primary reference sources are Stratum 1 clocks and are the best clocks and are at the top of the hierarchy. As you go down, you go to lesser quality clocks. Stratum 2 is the second layer. Up until this point, Stratum 2 clocks have been double-ovenized crystal oscillators. Telecom Solutions made the decision to go with a rubidium oscillator for their Stratum 2 clock in their TSG. I think the rubidium turned out to be much more stable than the crystal and really helped to improve the performance of the network.

In 1987, AT&T started investigating GPS and started building a system to use it in their network – again, I'm going to talk about primary reference sources in detail later.

In the late 1980's, SONET started to be deployed. SONET stands for Synchronous Optical Network. It was the new fiber-optics standard. The important thing is that the 's' in SONET is for 'synchronous.' Before this, fiber-optic systems had been asynchronous. At this point, the industry made the decision to make optical systems synchronous, and there are a lot of reasons for that. I think in the bottom line, it goes back to delay and the bandwidth efficiency. For those of you with an international interest, SONET is the North American version of SDH. SDH stands for "Synchronous Digital Hierarchy."

Also in the late 1980's, there were some large network outages that were related to network synchronization and related to some problems with BITS boxes. The bottom line of these outages was not a precise time and interval-type issue, it was an availability issue. But the outages helped focus the telecom providers on synchronization. They saw that synchronization problems could bring down their network and create major outages. It was really right about when I started with Bellcore, so it made me kind of nervous whenever I was working in an office, knowing that I could bring down the network.

As we moved into the 1990's (slide 11), a big development was the adoption of TDEV as a performance parameter. I'm going to talk about parameters as a separate topic a little bit later. Also, SONET rings became the architecture of choice for SONET deployment. This is important because it impacts timing distribution architectures. Originally, switches were used to distribute timing. This led to a very simple star architecture. As SONET was being deployed, we wanted to use SONET for timing distribution, but because it was in ring architectures, it is very hard to avoid timing loops. A timing occurs when a clock is disconnected from a primary reference source and somehow timed from itself. So SONET rings created a difficult planning issue.

Also in the early 90's a filter clock, Stratum 3E, was defined and built. As the industry was working on the performance specifications, it was clear that there was too much phase noise in the network and a clock that would filter out this phase noise was necessary. Up until this point most of the Stratum 3 clocks had been jitter filters, which meant their bandwidth was around 10 hertz. The industry decided we needed a clock that would filter to about 0.01 hertz. The 3E clocks that were developed were very neat pieces of engineering because there were some the very tough requirements on them. First of all, they needed a narrow bandwidth to do a lot of filtering, but also, when they had a good clean reference, we didn't want them generating a lot of wander, which implies a wider bandwidth. So there are a lot of design trade-offs to make both of those things happen.

TR-1244 was published by Bellcore and the ITU published G.812 in the early 90s. Up until this point, we had just had interface specifications and we didn't have any good detailed clock specifications. These documents were one of the first documents to say that this individual clock has to have this level of performance.

This year, we're seeing some primary reference sources using GPS with crystal being developed. There is a lot of excitement about this; it's helped drive down the cost of PRSs. Again, I'm going to talk about PRSs next. Let me jump into that.

PRS stands for "primary reference source." In the ITU terminology it's a PRC, a primary reference clock. They're at the top of the stratum hierarchy. Their main characteristics are an accuracy of 10^{-11} and low wander. The peak-to-peak phase movement at one second is required to be less than 10 nanoseconds.

At divestiture (slide 12), there was one primary reference source for the Bell system; it was located in Hillsboro, Missouri. It was a triplicated cesium ensemble. Sprint and MCI had their own PRSs. They chose to go with LORAN technology and had quite a few distributed throughout their network. At this time, the baby bells were taking timing from AT&T.

Since divestiture (slide 13), as I said, the other IXCs were using LORAN and continue to do that, although I think they've started investigating GPS. In 1985, Pac Bell decided that the quality of synchronization they were getting from AT&T, as it was transported over the plains and then the Rocky Mountains and then the deserts of California, was not meeting their requirements. So they deployed their own primary reference sources, and they chose to use cesiums verified with LORAN. They had four of those distributed throughout California. That was the first of the baby bells to "break away" from AT&T.

Then in the late 1980's, AT&T, as I said before, started moving to GPS. Instead of having just one PRS in Hillsboro, they decided to have 16 sites throughout their network. Their PRS had 3 rubidium oscillators in conjunction with the GPS receiver. Their primary reference clocks are quite a rack of equipment, with GPS receivers, rubidium oscillators, time interval counters, and a lot of software.

As we look now in the 1990's, we see GPS gaining wider acceptance. But there's also a lot of interest in cesium, at least in the baby bells. There are a few reasons for this, the main one being the antenna required for either LORAN or GPS. The baby bells are very risk-adverse. When they see an antenna on a roof, they don't see that as a way of bringing timing into a building, they see it as a way of bringing lightning into a building and destroying equipment in the building. Certainly you can have lightning protectors, and that helps, but the lightning protectors need to be grounded. The baby bells are also very process-oriented, and so there are a lot of rules about how those things are grounded. This drives installation cost up.

We're seeing manufacturers being very aggressive in pushing GPS technology and driving the cost down. But the installation costs have been up to four times the equipment cost. That makes it very expensive. Cesium has no antenna, so the installation costs would be much less. There have been rumors about low-cost long-life cesiums, although I'm not aware of any products that have been announced. So the installed cost for the different technologies could end up being fairly close, even though the equipment cost will be higher for cesium.

Another thing about GPS is that telecommunications people have never been completely comfortable with it. The Selective Availability issue and the fact that the DoD retains the right to mess it up to any level at any time makes people a little nervous. Also the fact that it is not a completely mature system concerns people. I just started subscribing to *GPS World* since a lot of my clients have been deploying GPS, and the first issue that I received talked about a problem with the PRN-12 satellite. It doesn't seem like it was a terribly serious problem, but it's the type of thing that causes a sync coordinator in a Bell Company to ask if he can trust his telecommunications network to this system.

I tried to put together some rough projections on slide 14. We've had some cesium deployment up until now, as you can see in the second column, and we've had some LORAN deployment up until now as well. Given the 1994 FRP, I would be surprised to see much more deployment of LORAN equipment. GPS has taken a big step this year. Again, a lot of that has to do with the aggressive pricing by the suppliers.

I think the project for the year 2000 for the total number of PRSs is a good guess (4000). I think we're going to get to where we have about 40 percent of our offices timed by primary reference sources. It eliminates the distribution problems that we were talking about before. But the breakout between cesium and GPS, I think, is the big question. The competition between cesium and GPS will be an interesting thing to watch. I just kind of took a guess here that I think GPS might win out a little bit in the end, but it's anybody's guess right now.

As I was going over this talk last night, I realized that I left off a fairly important topic of interest to this audience; and it goes a little bit to the introductory speaker about what are our requirements. Right now, we have an accuracy requirement of 10^{-11}. That's been around for a long time, since the mid-1980's. It is still our requirement, and I think it probably will be in the future. There's been talk of better accuracy, 10^{-13}, 10^{-14}, and I think NTT out of Japan has taken this issue to some of the ITU standards groups.

I'm an engineer and I have a little bit of scientist in me, and I think it would be neat to develop a 10^{-13} system just to say I did it, or we did it. But as an engineer, I need to know the cost-benefit analysis: What are we going to gain with going to 10^{-13}? People usually cite higher byte rate systems. As you go up in byte rate, the size of your unit interval (nanoseconds per bit) decreases.

But that's not a driver this accuracy issue. The highest bit rate we have defined now is OC-192, which is a 10-gigabit system. But the 10-gigabit system is just a point-to-point system. The point where you need the synchronization is on the payload signals that you're switching or cross-connecting. Those signals are cross-connected at either the 50-megabit level or the 155-megabit level. That 10-gigabit signal – and this is kind of what SONET is all about – is made up of lots of these 155-megabit signals. So it doesn't matter how high you go in bit-rate, you're still cross-connecting the 155-megabit signal. That's where the synchronization comes in, at the cross-connected signal. So the bit rate is a non-issue in my opinion.

There could be other things that drive future accuracy requirements. One new technology is called "ATM," Asynchronous Transfer Mode. Without going into a lot of detail, one of the things in ATM is a time-stamping mechanism. Right now, it is purely a frequency time stamp, but it's conceivable that it would be a more robust system, if it used a true time of day time stamp.

Having said that, I was going to mention this in the introduction, the clocks I'm talking about are just recovering frequency, they're not recovering time of day. I'll talk about time of day a little bit more later. Currently our clocks are a bunch of either phase-lock loops or frequency-lock loops that are chained together. So they're recovering time from an upstream clock and not time of day.

We have improved some of our performance specifications. In the 1980's, there was a single number for wander, 18 microseconds. It related to the buffer size for DS-1 slip buffers. Basically the specifications were written to prevent more than a slip a day, by controlling the wander to 18 microseconds a day. 18 microseconds is a pretty large number.

In the 1990's, we finally completed those wander specs down to intervals shorter than a day. Wander is specified using MTIE, which is a peak-to-peak wander within a given observation window. For DS-1 signals, which is the one-and-a- half megabyte signal – the MTIE for observation times of 1 seconds is 300 nanoseconds; for SONET signals, it's 70 nanoseconds; and for the primary reference sources, it's 10 nanoseconds. Again, I don't see too much driving need to get too much tighter in the future.

Additionally, holdover specifications have evolved over the years. Holdover is when these PLLs go into a flywheel operation after a reference that they were locked to goes away. In the 1980's, there was just one number on this flywheel operation. In the 1990's, we decided to break that one number into components. What we saw is that clocks were very sensitive to temperature; so we could take that temperature component, break it out, and it becomes the largest component. The drift and the initial offset can become small compared to that temperature component. It leads you to the realization that the clocks were actually performing much better than the specification, because normally we don't have the wide temperature variations.

As we look to the future, I'd be surprised if we tightened up holdover specifications. The future is always a tough thing to guess at, but right now, at least for SONET, it seems like we've nailed things down.

Another area of interest is performance parameters (slide 15). In the 1980's, we used two performance parameters, frequency accuracy and MTIE. In the late 1980's, we were using something called "RMS TIE." I joined Bellcore in 1988, so I don't accept any responsibility for this mistake. T1X1.3 quickly learned that RMS phase noise is a bad thing; it doesn't converge. We threw it out. This was an interesting time because we needed to make some big decisions. What we're finding out was there was too much wander in the network for our SONET systems to work. There were a whole bunch of issues that were interrelated; it was a very difficult problem to try to analyze. We didn't have a good measure of how much wander we had in the network, so we had to first pick a parameter to specify the wander in the network.

Working with Dave Allan and NIST, we chose TDEV. I must admit at the time I was a proponent of using a power spectral density parameter. I thought more information would be better. Since then, I've seen the light, and understand the power of TDEV to provide spectral information without being overly complicated.

As we get into the 90's now, we're nailing down a lot of definitions for parameters that have not been rigorously defined before. I want to credit one person in T1X1, Dan Wolaver, who is an old MIT professor. He's helped to bring some mathematical rigor to T1X1.3. We've nailed down a good mathematical definition for frequency drift and other items.

Another interest to a precise time group is our measurement methodology information (slide 16). Back in the mid-1980's, measurements were made with phase comparators and chart recorders. There is a company out of Rochester, New York, called Spectracom that puts these two together in a box and calls it a wander test set. We were still using these when I joined the group. We could get 100-foot-long tapes and we would stretch them out in the hallway and try to figure out what a clock was doing. This was not the easiest thing to do.

At this time, people in the industry were also using time interval counters that were hooked to printers. They'd get numbers; and they'd take the numbers and plot them. So this was getting a little bit more accurate, you had actual numbers you could work with, but it was still very difficult and tedious.

Finally in 1989, we programmed computers to control the time interval counters, and get the data electronically and automatically so that we could do analysis like MTIE and TDEV. Recently, there's been an integrated test set that does all this: Microwave Logic, which has since been bought out by Tektronix, developed a SONET test set called the SJ-300.

I put clock extractors on the slide. They're one of the banes of my life. Clock extractors serve a couple functions; they take data signals that have ones and zeros and create a square wave that is more useful with a time interval counter. They typically also do frequency division to give you a lower rate signal so that the edge crossing issue goes away as well. I have found them to be fairly unreliable and the largest source of measurement noise.

We're a little bit lucky in telecommunications because the level of noise we're measuring tends to be fairly high for wander: tens of nanoseconds. Therefore, we don't have to worry about things like the double-balanced mixer technique advocated by NIST. I think those techniques are possible, but it would be that much harder to make the measurements.

However, for high-frequency phase noise called jitter, there are some very tight specifications that are more difficult to measure. For example, there's a 0.01 unit interval rms specification for OC-48, which is a two-and-a-half gigabit signal. 0.01 UI at two-and-a-half gigabits translates out to about four picoseconds. That's a very difficult thing to measure. Companies like Microwave Logic have developed test tests to do this, and I think they take advantage of balanced mixer techniques.

Another issue for Bellcore is that we're having trouble verifying PRS performance. I have a cesium in my lab that has an accuracy specified at 5 parts in 10^{12}. I'm trying to measure the accuracy of GPS receivers that are specified to be at least as accurate, if not more accurate. I know I could buy a Hewlett-Packard cesium, but unfortunately I don't have the money. So we're looking at some cheap way to be able to verify accuracy performance for PRSs.

Finally, I will look into my crystal ball and share what I see in the future of timing in telecommunications (slide 18). The first item is pretty much a no-brainer. We definitely will see more PRS deployments. This goes back to the SONET deployment that is making it more difficult to distribute synchronization. So our synchronization coordinators want to either eliminate completely or minimize synchronization distribution, depending on who you talk to. The question here, I think, is which technology wins out in the end: GPS or cesium.

Time of day is something I have a question mark by. There's definitely a need for time stamping alarm events so that you can correlate them and figure out where problems actually are. Also time of day is need for billing. However, those applications don't have particularly tight time-of-day requirements, probably on the 10's to 100's of milliseconds.

Currently, I think people are going insert time of day at a few points in the network and then distribute it around using network time protocol (NTP). However, it seems if you had very accurate time of day, you could then use that for things like frequency synchronization, as well as other things such as encryption and secure digital signatures. The question is will the benefits of those applications justify the costs of much more time-of-day deployment.

PCS cellular seems like a big growth area to me. $7 billion has just been spent on the spectrum by these carriers. They're all going with digital technology. I think both of the digital technologies, CDMA and TDMA, have synchronization concerns. I think these concerns are related to both the frequency reuse issue between the cell sites; and also to hand-off issues as phones move from one cell site to another.

Another issue I see on the horizon is better monitoring. Right now, we send synchronization to another office and we assume that they're using it correctly. We've seen that improper synchronization can degrade performance, and there's a feeling that we need to do more to make sure that performance is not being degraded. However, we're not completely sure exactly how to get there. The introduction of SONET only makes this more complicated.

The other thing that I see in the crystal ball is international markets. The international folks, I think, are starting to accept the BITS concept and the idea that you need stand-alone clocks. I think they're taking synchronization much more seriously now.

In conclusion (slide 19), I think we've come a long way but we have a long way to go. The telecommunications synchronization personnel will have jobs for awhile. To me, that's pretty important, given where I am in my career. If the government shuts down, we can take a few of you folks, but not all of you.

Bellcore
Bell Communications Research

Progress of Timing In Telecommunications

Ron Brown
PTTI, December 1995

Outline

- Need for synchronization in telecommunications
- General milestones
- Evolution of specific topics
- Look to the future

slide 2

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Why Synchronize Telecom Networks?

- General
  - Delay -smaller buffers
  - Bandwidth efficiency -bandwidth is not free
- Specific
  - Data integrity -slips, jitter
  - Frequency reuse - cellular

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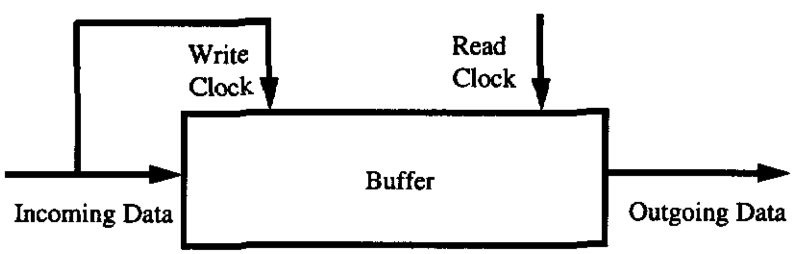
slide 3

Elastic Stores

- Slip buffers, desynchronizers, pointer processors
- Read clock may be filtered version of write clock or independent



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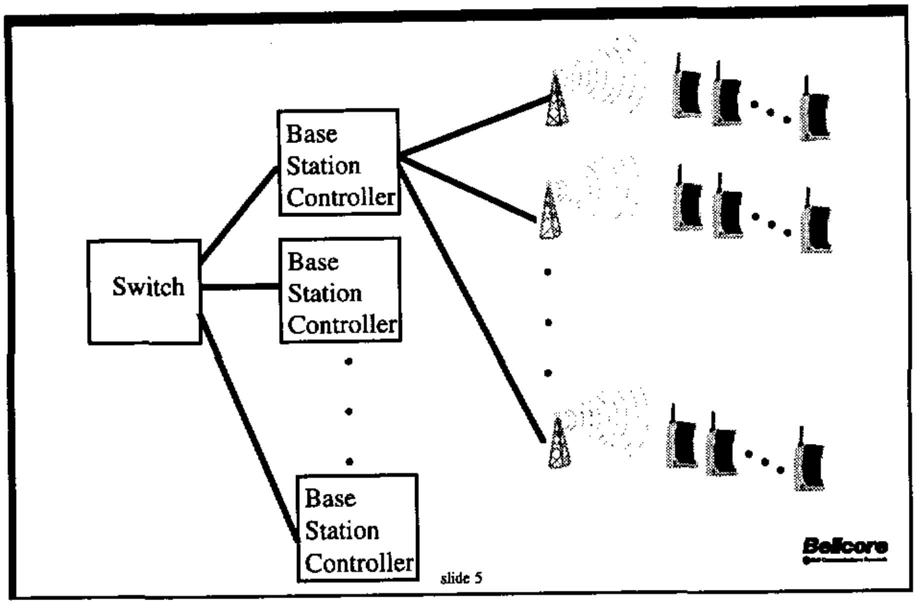
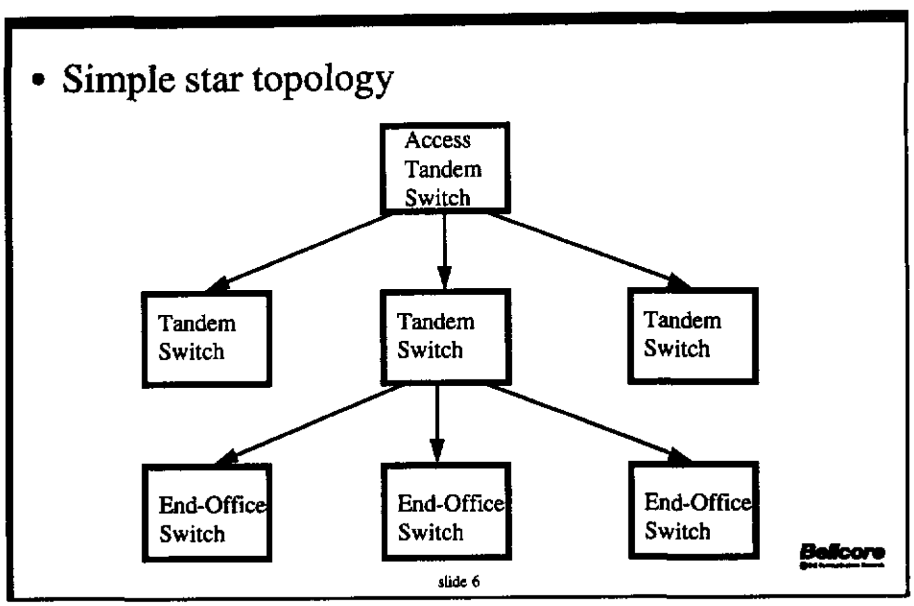
slide 4

Cellular Networks

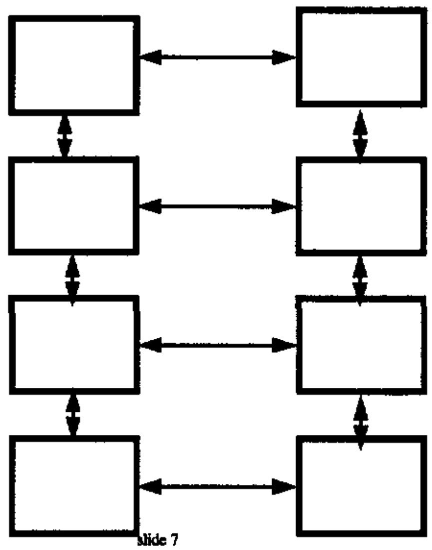


Switched Based Timing Distribution



SONET Based Timing Distribution

- Complicated rings



slide 7

Some Rough Numbers

- Baby bells - 1000 switching offices each
  - 7 baby bells & GTE
  - many independents with a few to 100 offices
- IXCs
  - 10s to 100 switching offices
  - also non-switching offices - 10s to 100 as well
- Large number of private networks
  - large variety in size
- Cellular -lots in the future

slide 8

Milestones of the 1970s

- 1972: Hillsboro triplicated Cesium ensemble
  - Analog network synchronization
- Early 70s: digital transmission equipment: T1 carrier
- Late 1970s: digital switching developed

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slide 9

Milestones -1980's

- Early 1980s: BITS Concept
- 1984: Divestiture
- 1985: Pac Bell deploys Cesium PRS
- 1986: True BITS -standalone clocks (TA-378)
- 1986: Rubidium ST2 clock
- 1987: AT&T decides to go to GPS
- 1988-90: SONET starts to be deployed
- 1989,90: Large sync related service outages: SS7

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slide 10

Milestones -1990's

- 1991: TDEV adopted by T1X1.3
- SONET rings architecture of choice
  - complicates sync planning
- 1992: ST3E filter clock developed-SONET driven
- 1993: TR-1244 "Synced Clock Requirements" published by Bellcore
- 1995: PRS using GPS with crystal developed

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slide 11

PRSs at Divestiture

- PRS at top of hierarchy
- AT&T 1 PRS in Hillsboro, MO
  - triplicated Cs
- Sprint & MCI
  - LORAN-C
- Baby Bells take timing from AT&T

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slide 12

PRS Since Divestiture

- 1989: AT&T moves to distributed GPS/Rb
- 1980s: Other IXCs use LORAN
- 1985: Pac Bell deploys 4 Cs verified w/LORAN
- 1990s: GPS gaining acceptance
- Interest in low-cost, long-life Cs
  - no antenna

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slide 13

Rough PRS Projections in 7 Baby Bells

	Cs	LORAN	GPS	TOTAL
• 1990	10	10	1	21
• 1995	16	128	415	559
• 2000	1500?	200	2300?	4000

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slide 14

Performance Parameters

- 1984: Accuracy, MTIE
- 1988: rms TIE (!)
- 1991: TDEV adopted with help from NIST
- 1995: Defined methodology for frequency drift

slide 15

Measurement Techniques Evolution:

- 1985: phase comparator & strip chart
- 1987: Time interval counter and printer (!)
  - clock extractors
- 1989: Computer controlled time interval counter
  - computer programs for MTIE, TDEV analysis
- 1993: Integrated Test Set (SJ-300)

slide 16

Measurement Techniques Issues:

- Enough wander - mixer techniques not necessary
- Jitter measurements for high bit-rates harder
  - 0.01 UI rms at OC-48 = 4 picoseconds !
- Trouble verifying PRS performance
  - 10e-12 hard to measure

slide 17

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Crystal Ball

- Greater PRS deployment
  - eliminate distribution related issues
- Time-of-day
  - where? distribute with NTP? accuracy?
- PCS/Cellular
  - biggest growth area
- Better monitoring
  - get away from "send and pray"

slide 18

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Conclusion

- *We have come a long way, but we have a ways to go.*
- *Telecommunications sync personnel will have jobs for awhile.*

slide 19

QUESTIONS AND ANSWERS

DR. GERNOT WINKLER (USNO, RETIRED): *Could you put the slide back on evolution* of performance? The 18 microsecond per day wander is, of course, as you mentioned, the allowance for one slip of one frame per day. That requirement necessitated the absolute accurate specification of 10^{-11}. In other words, that accuracy requirement comes from concern about the international connections, or the intercontinental connections.

Now if you look at development where you go to 300 nanoseconds, it goes to 300 nanoseconds, 70 nanoseconds, and so on at these increased bandwidths and higher communication speeds, I would expect that this would also then mean there would be a greater accuracy requirement for that. In other words, for the operation within your network, there is no benefit in having that accuracy. But for the interconnections between that, particularly accuracy, – so the accuracy requirement is an external requirement, and not an internal requirement.

RON BROWN (BELLCORE): My take on that again is that the higher bit rate signals, you can really view them as point to point; the 10-gigabit signal is point to point. You're going to need a buffer in the front end of your SONET equipment that needs to accommodate jitter.

One of the slides I skipped (slide 4) discussed elastic stores Elastic storage is the concept, I *think, that probably most engineers are familiar with.* An elastic store is a buffer that has a separate read and write clock. Elastic storage has a lot of different applications. One application is a DS-1 slip buffer. In a DS-1 slip buffer, the write clock is from the incoming data, the read clock is from the system clock. So if those two are different, eventually this buffer is going to overflow or underflow.

In the SONET system, there are actually several layers of these elastic storage. The first layer, in what I call the front end of the equipment, you have the relationship between the write and read clock in that the read clock is a filtered version of the write clock. It's not tied into the system clock. *So if the system clock is different than the clock on the received data, it* doesn't affect this buffer. It's the buffer at the next layer down that can be impacted. That next layer down is called the "point or processor buffer." That works on the 155-megabit or the 55-megabit signals. It's always going to work on the 155-megabit signals regardless of the line rate.

DR. GERNOT WINKLER (USNO, RETIRED): So if I understand you right, that suspicion that I voiced is not valid because you have buffering in an entirely different way.

But there is a second comment which I want to make, and that goes back to a need for having more precise definitions of these different requirements. You have five levels, and the five levels are to operate on the same frequency; to be on the same accurate frequency, an additional requirement which, of course, costs money; to be synchronized; to be synchronized in time – in other words, not allowing any steps, but without resolution of delays; and finally, to be on UTC, the time of day. If there is any requirement to be on time of day, then of course the use of GPS is far superior to the use of just the cesium standard.

RON BROWN (BELLCORE): Right. In the competition between cesium and GPS, I think *time of day is a critical issue. If there is a time-of-day requirement, and that time-of-day* requirement gets tight enough where you can't distribute time of day, then GPS is clearly the technology of choice. I've seen a lot of articles by NTT and distributing time of day, and it seems like they can get fairly good accuracy. But if you need a nanosecond, or 10-nanosecond accuracy, I don't think you're going to be able to distribute it. So if that requirement becomes real, then GPS definitely will be the winner in that technology race.

The worse scenario, at least from my clients' point of view, is that that requirement isn't clear now, they choose cesium; the requirement becomes a requirement later on; and then they have to employ GPS on top of the cesiums they've already bought. But right now, there's no drive for 10 nanoseconds absolute UTC accuracy. Certainly if you have that, you can drive everything else into it. It's not a bad argument to say that why don't you just get that so that you derive everything else, and then you don't have to worry about where things go in the future. So, there's definitely a strong argument that can be made for GPS and getting that capability. By the way, I don't want to discourage people from developing 10^{-13}, 10^{-15} cheap receivers. I'm sure if it becomes cheap enough, we'll definitely take advantage of it. So, there's always a cost benefit. As the cost comes down, it becomes easier to justify.

CAPTAIN STEVEN HUTSELL (USAF): You bring up a very good point about the amount of confidence that civilian users have in using GPS for time transfer. And I think it's important to point out that as with any costly expensive system that people decide to use for precise timing, whether it's a cesium ensemble, LORAN, or GPS, a lot of the confidence level that the user will have will greatly depend on the application and the implementation. I think it's important to point out that there are relatively simple techniques to identify and catch problems similar to what you were mentioning about PRN-12, as was mentioned in the *GPS World* article. Those include high-sampling checks of the parity and the help settings in the navigation message. That's probably a good first line of defense, and a good second line of defense would probably be something similar to a receiver set that could track all satellites in view and easily isolate a problem bird such as PRN-12.

RON BROWN (BELLCORE): Thanks for the input. We have tried to write requirements to make things as robust as possible, but we're not GPS experts. So, maybe I'll try and get with the GPS experts to get some more of those details.

RON ROLOFF (DATUM): One more question. You mentioned long life in cesiums. What is your long life?

RON BROWN (BELLCORE): My synchronization coordinators tend to be a little bit older group, so their definition is "As long as it's going to take me to retire!" But seriously, the number that I have heard thrown around is 15 years. I don't know if this is realistic or if it just the cesium suppliers trying to compete with the GPS suppliers. But, 15 years is the number that's getting people excited.

RON ROLOFF (DATUM): Why is that different than applied to your other equipment? Or is it?

RON BROWN (BELLCORE): You mean like other telecommunication equipment?

RON ROLOFF (DATUM): Yes.

RON BROWN (BELLCORE): Okay, telecommunication equipment life cycles is a bigger can of worms than you might realize. There are bigger depreciation cycles for different areas. So public utility commissions sometimes require 30-year depreciation cycles, whereas a normal business might look at it on a 5-year depreciation cycle. So, there's a bunch of depreciation issues there that are related to regulatory issues that I don't completely understand.

Then there's just a replacement cost. If you just look at lifetime cost of a product, you've got to look at how often it needs to be retrofitted, and how much that's going to cost you to do it.

SAM STEIN (TIMING SOLUTIONS CORPORATION): I would like to pursue this issue of the time synchronization in a network as opposed to frequency synchronization. I believe what's driving the interest of NTT in Japan is that the wander over 1000-kilometer networks is on the order of many microseconds. This is a substantial fraction of the allowable wander budget in the network. The issue being the ability to construct signals at the user end – to be able to reconstruct – in the phase-lock loop. So they would attempt to drive the wander due to – and alignment down from five microseconds to some small fraction thereof. – –. I was wondering whether there is support for that kind of approach within the United States in SONET and whether this is within long-term direction.

RON BROWN (BELLCORE): Let me raise a few issues. First SONET is a little bit ahead of SDH and there has been more SONET equipment deployed than SDH equipment. Anytime you look at changing the SONET standard, you are looking at possibly retrofitting a lot of equipment. So the carriers have to be convinced that the benefits are going to be significant to incur that cost, whereas the cost is maybe less for the SDH people because they do not have quite as much deployed. There is interest in going to higher accuracies; it has been brought up in T1X1.3 and when it gets brought up people say that it is interesting, better seems better, lets pursue that, and try and push for that. Which is not to say that won't happen in the future, but it is not clear to me what the NTT goal is.

DR. GERNOT WINKLER (USNO, RETIRED): I thought you were going to mention the Thursday evening seminar about "Robust Timing" techniques, which has a direct implication to what we have discussed here.

SAM STEIN (TIMING SOLUTIONS): I am going to talk about government interests in pursuing exactly that technology for reducing total wander across SONET links.