TIME AND FREQUENCY STANDARDIZATION

by

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I take great pleasure in coming over to these rather hallowed halls of the Naval Research Laboratory. May I remind you that our Naval Observatory, which CAPT Hankey represents, is perhaps hallowed squared. It is one of the real beginnings of scientific endeavor in the United States. There has been a common Naval tradition across the wide world going back into the 1200, 1300, and 1400 period of history when the Dutch, the Portuguese, and the British Navies became prominent. They ran into a very substantive need for fairly accurate time, that is, if they wanted to get back home to the wife and kids. Some of you may remember the famous stories of trying to find a chronometer, and how they looked and what they were like when first built, and how they cheated the chap that finally made it work, for some 10 or 15 years, out of his stipend, and that's a story in itself. Like most great inventors, he finally got his money just as he was about to die.

I am not an expert on these things, I am an ordnance man, missile and fire control educated. But in the course of a rather misspent Navy life, I constantly have run into bits of science here and there. I can recall working with Dr. Draper at M.I.T. when we were first postulating the possibility of an inertial navigation system, and frankly, that was treated with the same credibility as a chap who might have been talking to a college physics group in the mid-40's, exploring the possibility of uranium fission.

I well remember at the PG school when my physics professor took an afternoon off to talk to us about these oncoming possibilities and we laughed at him. Of course that was about 1943, but it wasn't very long after that when we had some very positive proof that it was not anything to laugh about. Underneath all of this is basic science and the very tight little specialty you're here to work with and contribute to. I must say that we have come a long way from the water clock, the sand clock, and the hourglass, to the things that we are doing now. Precise time measurement is absolutely fundamental in modern communications and navigation and many other areas of modern life. This technology requires a degree of precision that has always seemed unobtainable. Because the Navy has recognized its importance, it has vigorously taxed its budget with the pressure necessary to support this technology. In turn, these improvements have fed back into such systems as LORAN-A, LORAN-C, OMEGA, and a worldwide communication network--not to mention the cipher and security systems, in which one mistake made at a nanosecond rate renders all the output thereafter worthless.

To address the bare fundamentals, it is essential to remember that almost every standard used is time-relevant, as shown in Figure 1. Even man has a time-relevant base. In past attempts to measure accelerations, a system was considered respectable if it could measure down to parts in 10^8. But today, even a "poor man's inertial system," a system that the average commercial airplane can afford, as opposed to a full military system, is being built regularly. It is visualized that one can eventually get a still cheaper system (for, perhaps \$1,000 or \$1,500) that will provide fundamental navigation for the pilots of the \$50,000 to \$100,000 machines that are regularly killing people around the country, because they are where they do not belong or because they are not where they think they are.

It is obvious that all these fundamental quantities, even in the electrical worlds, are time-related. Some question remains as to whether

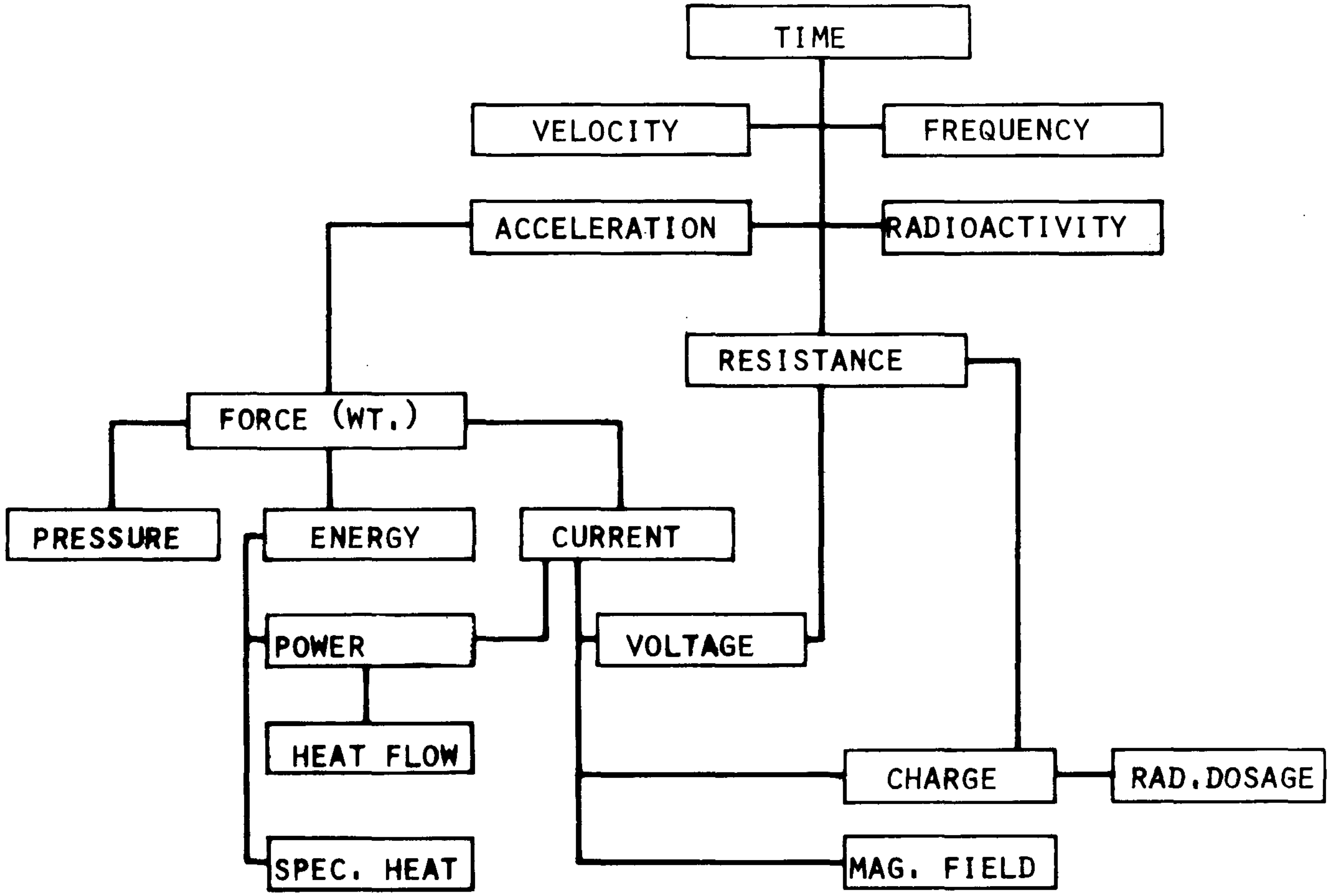

Figure 1. TIME

resistance is time-related, per se. It is known that electrical current is a time measure domain of Qdt, therefore it can be said that E = IR or $R = \frac{E}{I}$, which gets into a time base, depending on how the standard is set.

The timing precision that has been required tends to follow a pattern along the lines shown in Figure 2, which illustrates the accomplishments of the time specialist, or scientist, who devotes himself to this field. Accomplishment is achieved in clumps, and the result is a step function where a jump is made. That is to be expected--the jumps from a wristwatch to a chronometer to a cesium clock are significant.

At the same time, in the normal role of nature, invention tends first to follow what is available and then to drive the system; the requirement often is established by the capability. At the present time, innovative ideas to move that line up are scarce, and, as a result, in the 1980's the requirement may be driving the technology instead of technology pulling the requirement up to it, unless there is another breakthrough.

Is there a quantum of time, as there is a quantum of everything else? Is there finally a spot where one cannot have half an interval? It is hard to visualize one part in 10^{24}. In postulating a protective defense system against an inertially navigated ICBM, it was figured that if the Earth could be moved roughly 100 to 150 miles off its normal rotation axis, the bomb would not get the message and would go on in inertial space coordinates to land off target. But the number of 45,000-pound-thrust jet engines required to move the Earth off its axis was about 10^{24}, an enormous number of engines. But then, if the Earth's axis could be shifted in less than 15 minutes, the bomb would overfly or underfly, but all the people would be flat on their faces. We must push on in pursuit of accuracy, because one can predict right now that the technology needs may well overrun technology accomplishments if the current pace is maintained.

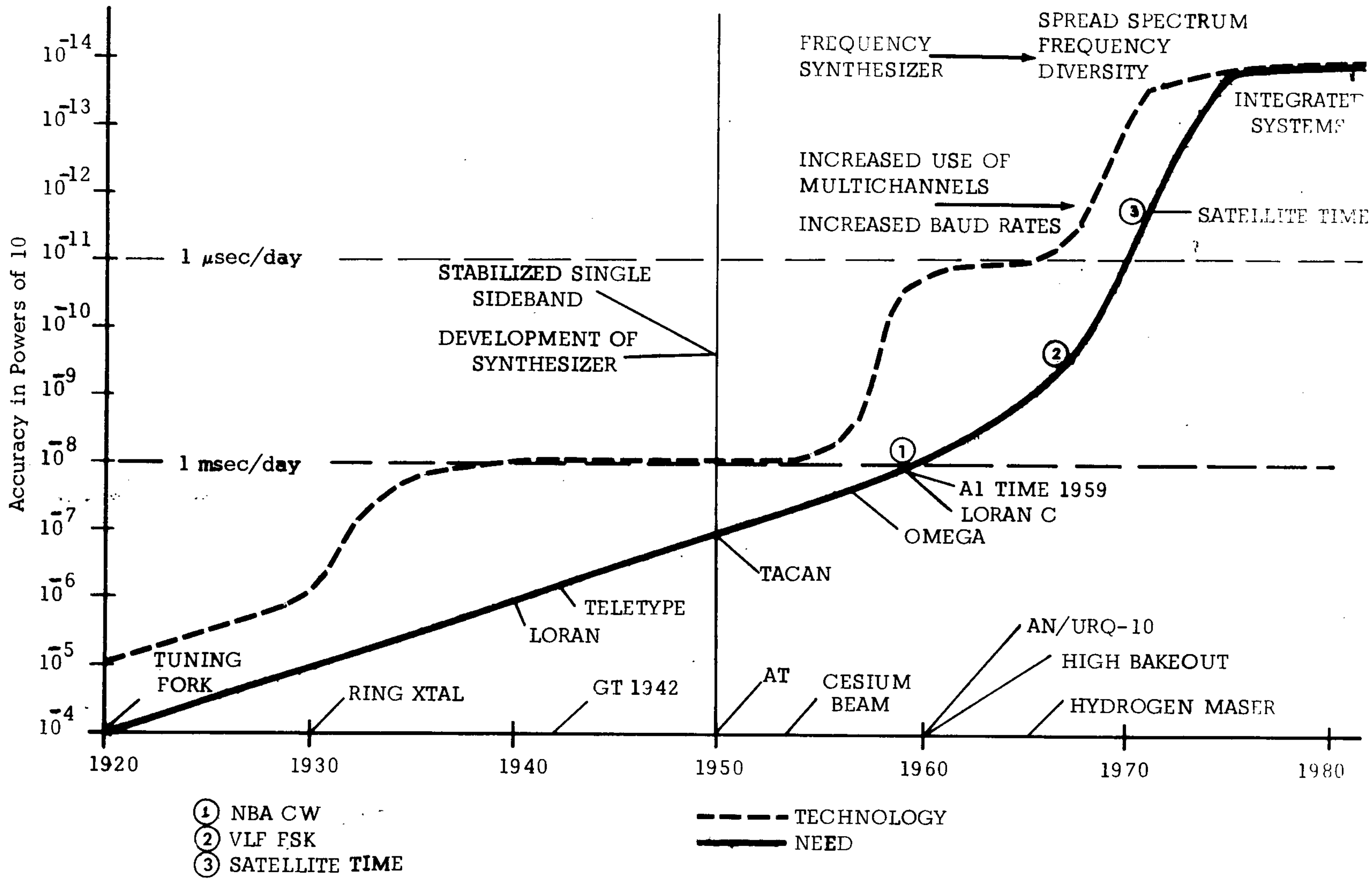

Figure 2. TIMING — NEED VERSUS TECHNOLOGY

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The contemporary instrument for accurate time checking measurements is the cesium clock. We fly these clocks around the world as needed. When the courier flies his clock, his errors are computed at one end; he takes the clock from station to station (Figure 3), and against it as his standard, measures everyone else's time as he goes by. He then returns home, which closes the loop, and then advises each station of its current error situation. One does not merely put the key in the machine and move the hands up, because that screws up the works, figuratively, just as it does on a chronometer. The clock is left alone, but the error is established.

However, flying clocks around (Figure 4) has become a nuisance, since airplanes are subject to highjacking and couriers carrying electronic equipment are regarded suspiciously at various borders. A somewhat better system is now evolving.

This plan is, in part, shown in Figure 5. The digital systems operating in the communication world can transmit time within their own capability; the defense satellite communications system becomes such a system. As a result, the problems created by foreign custom agents, flight schedules, airport staffs, and aircraft failures are eliminated. Attention can also be redirected to any given site by a proper use of antennas and satellite communication. The system is currently operational, more or less, claiming a time signal accuracy to one-tenth of a microsecond on the network from the Naval Observatory, coming out of Brandywine to the DCSC terminal at Camp Roberts, California, then out to Oahu, and over to Germany and Guam.

The next step is to transfer this time to the local users. The first effort is being made at the Naval Communications Station, Wahiawa, Hawaii; this operation was surveyed the first week of October.

The system is a little complex (see Figure 6), but the main point is that once the time signal is brought into the local station, the local user can process it, and use it to update his own equipment, and then provide this additional service for various supporting equipment. The

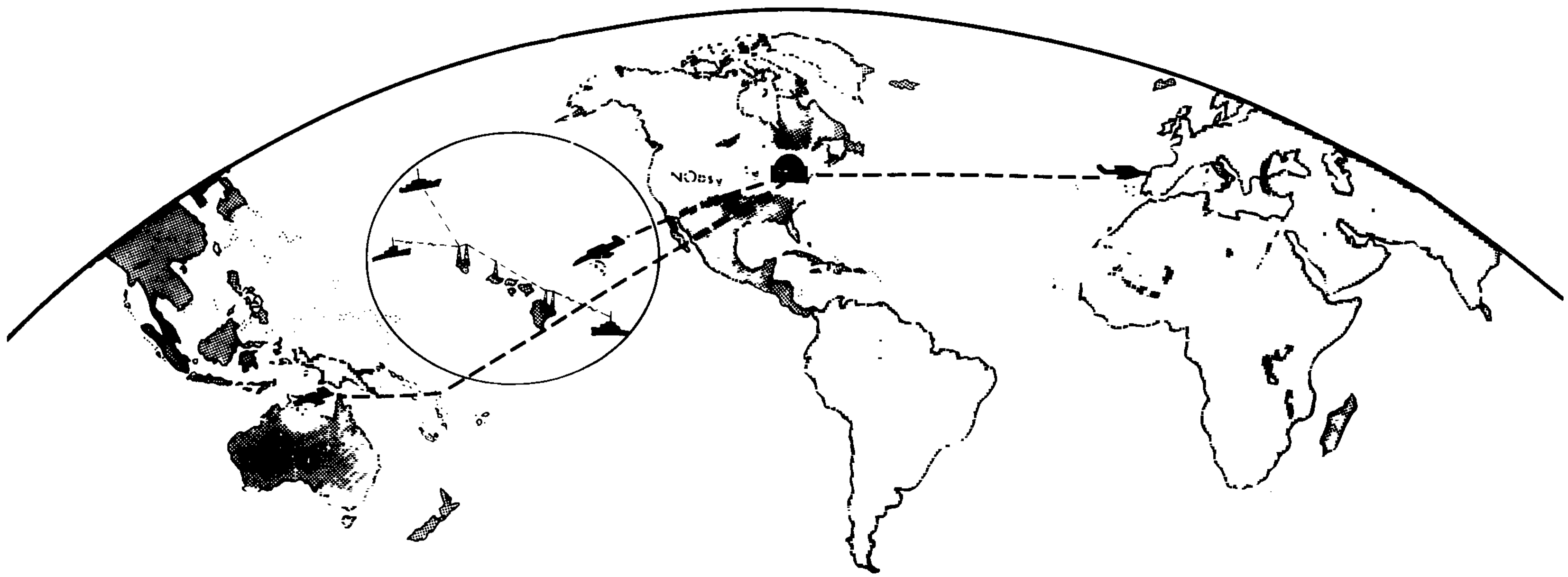

Figure 3. PRECISE TIME SYNCHRONIZATION SERVICE (PTSS)
WORLD DISSEMINATION

Figure 4. CESIUM CLOCK STRAPPED IN FIRST CLASS AIRLINE COMPARTMENT

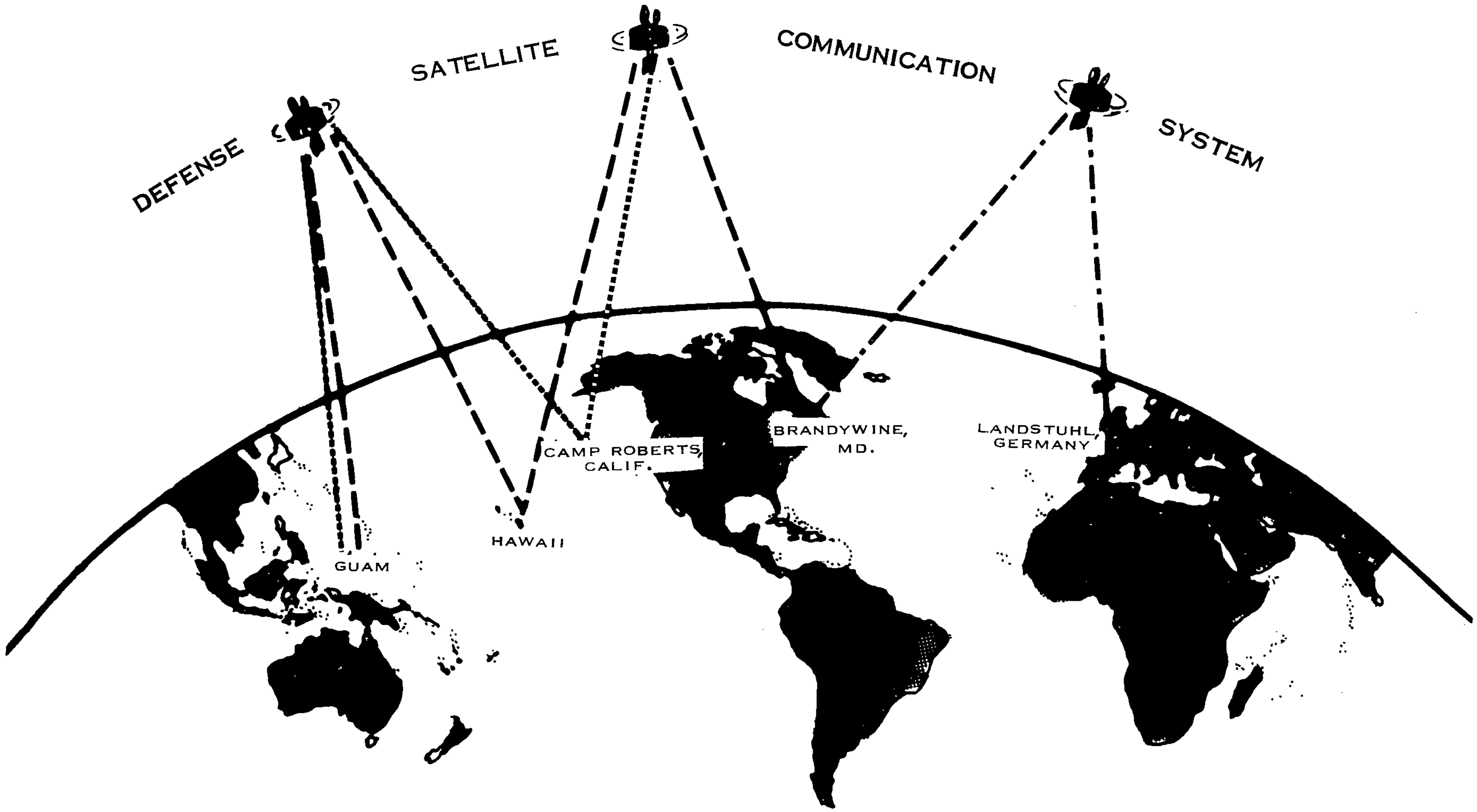

Figure 5. PRECISE TIME AND TIME INTERVAL (PTTI) WORLD DISSEMINATION

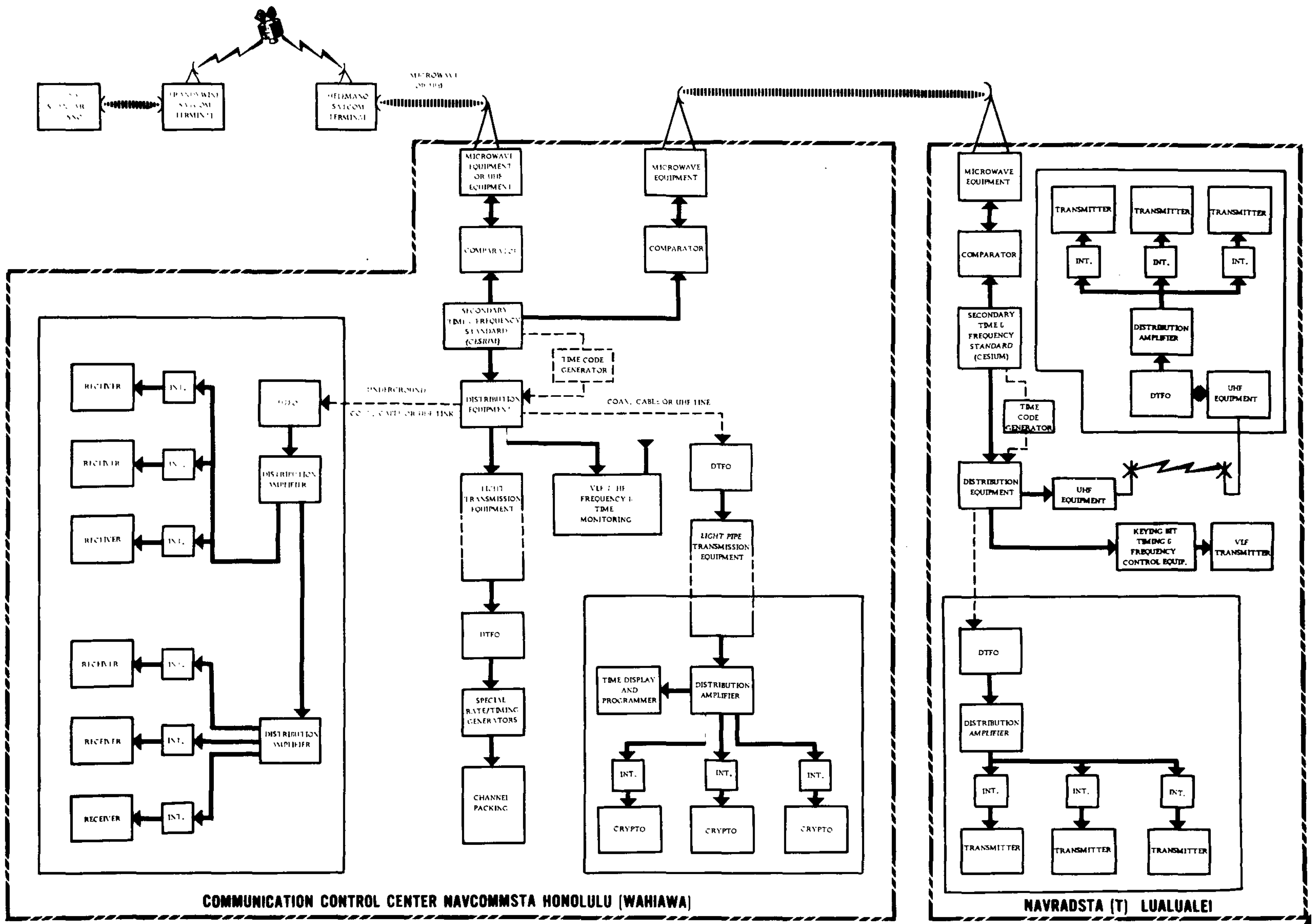

Figure 6. PRECISE TIME AND FREQUENCY LOCAL DISTRIBUTION FOR NAVCOMMSTA

system will provide inexpensive, relatively reliable, all-weather, sea and air navigation improvements, just because of the availability of precise time and time interval. The modern navigation system is already fairly accurate, but unprecedented accuracy, almost beyond the immediate needs, is achieved by pushing one order of magnitude higher.

Some current uses of precise time and time interval applications are shown on Figure 7. The VLF transmissions are used to site Navy ships, and the oil companies are also using them to site their oil drilling rigs. As synchronization of all these platforms is enhanced, many of the time losses in calibration will be eliminated and many of the restraints of the previous systems disappear.

It might be mentioned here that the digital data rates under good control can perhaps go up from 2400 baud to as high as 9600 baud or better; however, the accomplishment of these rates directly depends on absolutely accurate knowledge of the baud-to-baud time rate. International color television transmission also depends on this knowledge; i.e., to bring in real time color television at both ends, the oscillators and color separators must all be accurately synchronized.

Some potential uses of precise time and time interval applications are shown in Figure 8. It is now envisioned that once the system is pretty well operative, users will have relatively simple equipment to take advantage of it. The capabilities of a new and simple collision avoidance system will encompass more than safety considerations, which are so essential and are becoming more so as the air traffic increases. In a sense the system will help decrease the traffic problems or help absorb the traffic because of better time control and better guarantees that the aircraft operator will obey precisely the instructions of the air controller and that the FAA controller will have a higher degree of confidence for using his time spectrum availability relative to his runways. For example, when pilots are being brought aboard an aircraft carrier at between 20- and 30-second intervals, the pilot who is 5 seconds late sends a 5-second transient

- **NAVIGATION/SHIP POSITIONING**
  - OMEGA
  - USE OF VLF TRANSMISSIONS
  - PRECISE SITING FOR OIL DRILLING
- **INCREASED EFFICIENCY OF POINT-TO-POINT DIGITAL COMMUNICATIONS**
  - REDUCED LIMITATIONS ON SYNCHRONIZATION
  - DIGITAL INCREASE 2400 - 9600 BAUD POSSIBLE
  - REDUCED TRANSMISSION LENGTHS
- **PRECISE CRYSTAL OSCILLATORS, SYNTHESIZERS**
- **RATING OF OSCILLATORS**
- **COLOR TV TRANSMISSION/RELAY**

Figure 7. PRECISION TIME AND TIME INTERVAL APPLICATIONS

- **EFFECTIVE COLLISION AVOIDANCE SYSTEMS FOR AIRCRAFT**
  - SAFETY
  - INCREASED AIRPORT CAPACITY/FEWER LANDING DELAYS
- **REDUCED COSTS FOR SKIN PAINT RADARS**
- **MORE EFFICIENT USE OF THE RADIO FREQUENCY SPECTRUM**
- **FURTHER LONG LINES COMMUNICATION EFFICIENCY**
  - RECENT RATE INCREASES NOTED
- **INFORMATION SYSTEMS**
  - LINKAGE OF COMPUTERS
  - REDUCED BUFFERING
- **TIME CORRELATION OF DISTANT GEOLOGIC/GEODETIC/ASTRONOMIC EVENTS**
- **THROUGH IMPROVED SYNCHRONIZATION, COMMUNICATION SYSTEMS WITH**
  - ANTI-JAM/LOW INTERFERENCE QUALITIES
  - LOW COST SECURE SYSTEMS FOR POLICE OR INDUSTRY

Figure 8. POTENTIAL PRECISION TIME AND TIME INTERVAL APPLICATIONS

down the chain and out to 30 airplanes; the 5-second delay may eventually entail an emergency airborne refueling for the thirtieth plane.

It is now believed that the radar skin-paint approach so commonly used may decrease in importance, perhaps almost to the point of obsolescence, when an airplane can accurately report its position. The skin-paint radar, which just closes the loop on relative motion, is a pretty expensive installation at airports and many other operations, where it presently is the final unit that links the relativity of all people in the grid together.

Higher precision would also lead to better use of the RF spectrum. At the present time radio operators are filling 3,000 kHz bandwidths with the human voice, speaking at from 250 to 330 words a minute. That is a poor use of 3 kHz when right now 1200 words a minute are pumped out with 10 or 12 simultaneous teletype circuits operating in the same bandwidth, and there is absolutely nothing technical to prevent a rate 3 to 4 times higher. Theoretically, one could go almost 6 times that, but the system noise level keeps the rate to 4,500 to 5,000 words a minute. When these machines of precise time control are built and working exactly to a part in 10^{11}, an almost infinite number of words can be put on the telephone or communication net by going back to codes instead of ciphers, which would envision a memory that's infallibly accurate. One could preposition anything in the memory--even the entire Bible if it were so prearranged that, when "dit da" was sent that meant the Bible, and both sender and receiver could read it. So there is really no fundamental limitation by bandwidth, if one has control of time at the computer level, both input/output end, and of memory.

A great many people are finding themselves very much involved in time. The astronomer and the geophysicist are now more accurate with their solar activity work and their correlation of earthquake information because of precise time. Reference is made to the possibility of low-cost security systems for both public and private sector communications, which, again, would be dependent on decoding and encoding, so that the common link is to know where one is at exactly the same time as somebody else who is far away. This goes right back to the navigator who tried to work longitude from a reference that he controlled only by knowing his time, and we are back to the chronometer where it all began.

The current worldwide distribution of precise time and time interval is shown in Figure 9.

In several ways, past requirements were well supported by those old fashioned multi-millisecond broadcasts. Many have read the familiar WWV, NSS, and NAA time signals, which replaced the old custom of shooting a noon gun in every major port, by which every ship in the harbor could check its chronometer. But our past requirements have been superseded by requirements far, far above this order of magnitude, now in parts of a microsecond, where a few milliseconds used to be good enough. For this moment and possibly for the next 5 to 8 years, it can be said that the technology of the present capability is in step with any forseeable requirement; however, this matching pace may not continue. The next step toward a greater precision comes up that S-curve of learning with great difficulty, but it is certainly a worthwhile challenge.

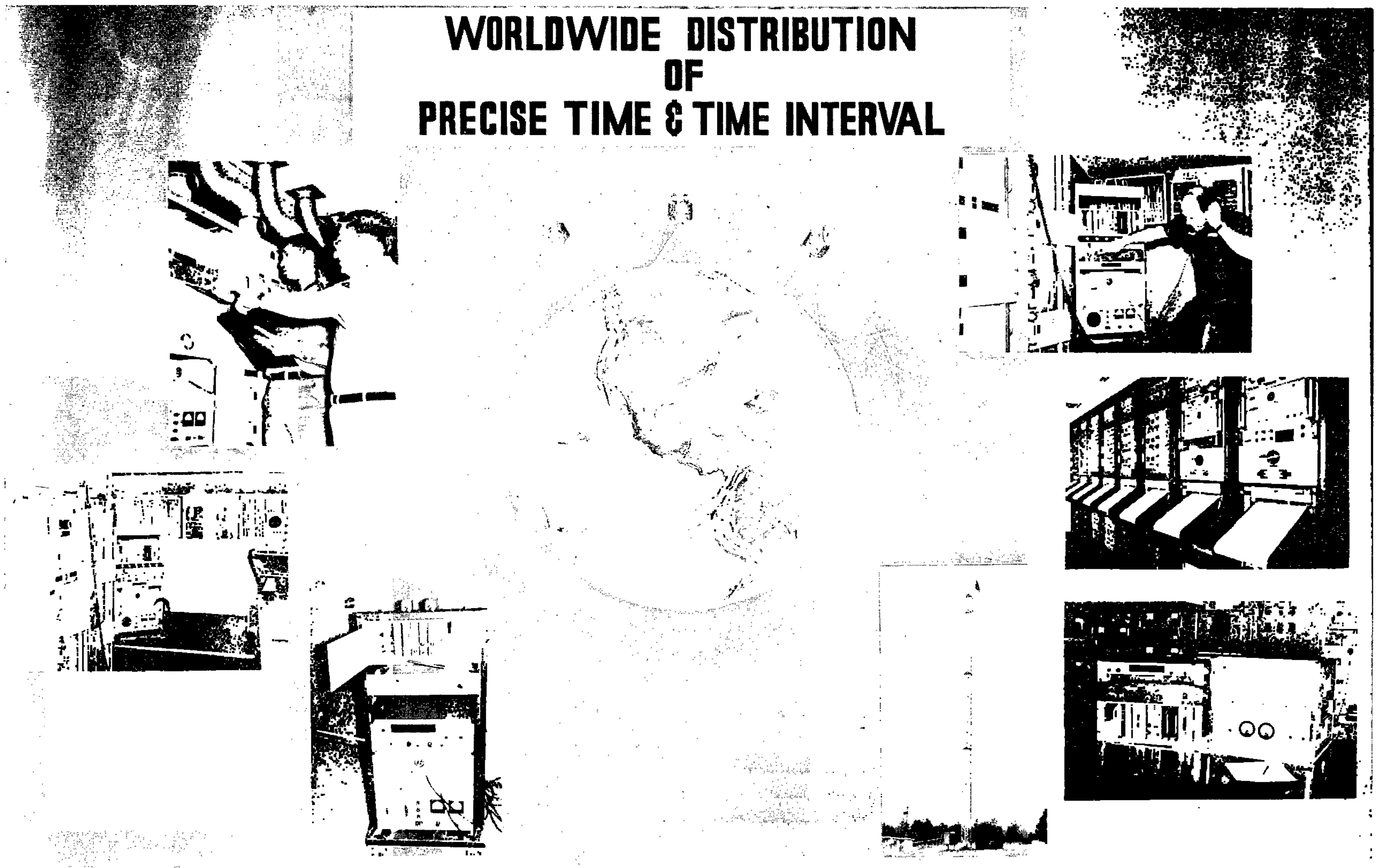

Figure 9. WORLDWIDE DISTRIBUTION OF PRECISE TIME AND TIME INTERVAL