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DIGITAL FREQUENCY CONTROL OF SATELLITE FREQUENCY STANDARDS

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ABSTRACT

In the Frequency and Time Standard Development Program of the TIMATION System, a new miniaturized Rubidium Vapor Frequency Standard has been tested and analyzed for possible use on the TIMATION IIIA launch, scheduled for early 1974, as part of the Defense Navigation Satellite Development Program. The design and construction of a Digital Frequency Control by NRL, was required to remotely control this Rubidium Vapor Frequency Standard as well as the quartz oscillator in current use. This control must be capable of accepting commands from a satellite telemetry system, verify that the correct commands have been sent and control the frequency to the requirements of the system.

The Digital Frequency Control consists of several daughter boards mounted on a mother board. The various daughter boards process the incoming digital information, convert to an extremely stable analog voltage; convert it to the proper levels for use by the frequency standard, and route it to the appropriate frequency standard. The Digital Frequency Control was designed to control one quartz oscillator and two Rubidium Frequency Standards. It makes extensive use of low power miniature TTL circuitry and hybrid miniature D to A converters to keep size and power consumption as low as possible. Control circuitry not in use is turned off and, except for the command system, the Control is redundant. Special isolation circuitry has been incorporated to protect the digital-to-analog converter from being falsely triggered by noise or spurious signals.

Several modifications must be performed to the Rubidium Vapor Frequency Standard to allow it to be compatible with the Digital Frequency Control. These include the addition of a varactor to voltage tune the coarse range of the "flywheel" oscillator, and a modification to supply the "C" field current externally.

Quartz oscillators in TIMATION I and II used a motor-driven glass capacitor for tuning, however the oscillator to be used for TIMATION III A uses a varactor which can be directly used with the Digital Frequency Control.

The Digital Frequency Control for the Rubidium Vapor Frequency Standard has been successfully tested in prototype form. Work is now being done on a flight version for TIMATION IIIA.

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INTRODUCTION

The TIMATION satellite navigation project depends on an ultra stable oscillator in the satellite as a basis for its accuracy. TIMATION I and II successfully used quartz oscillators, especially built by Frequency Electronics Inc. for space use.[1,2] The TIMATION III satellite (Navigation Technology Satellite I) is scheduled for launch in early 1974 as part of the Global Positioning System Program. Figure 1 is a picture of the satellite which will also have a quartz oscillator as its primary frequency source; however while TIMATION I and II used mechanical tuning (stepper motor), TIMATION III will use varactor tuning controlled by a Digital to Analog Converter. In addition two experimental Rubidium Vapor Frequency Standards are being tested for possible use.[3,4] These units would also be controlled by D/A converters[5], which, with associated circuitry is combined in the Digital Frequency Control. The Frequency Standard System will be configured to provide redundant frequency sources, with the ability to select, by command, one of the three RF outputs for the experiment. A system block diagram is shown in Figure 2.

Digital Frequency Control

The Digital Frequency Control[6] is a circuit which converts digital information to analog signals which control the frequency of various frequency standards. To do this effectively the output stability must be low compared with the frequency sensitivity of the frequency standard control. Extensive use has been made of components and techniques that have been developed and refined in the past few years.

The Digital Frequency Control has four main functions: dc power control, digital word control, D/A conversion and analog control voltage processing. As the primary frequency source, the Quartz oscillator has dc power applied to all times. It uses +15 v for the oscillator, ±15 v for the D/A converter and operational amplifiers and 5 v for the logic control. The Rubidium units use 28 v as well as ±15 v and 5 v. Only one Rubidium unit can be turned on at any one time. Separate regulators are used for these voltages, except the logic supply, to provide redundancy. The command system and associated logic circuitry is not redundant. The oscillator system will continue to run in the event of a command system failure, but there could be a frequency shift.

The Digital Frequency Control has four switches to control these voltages. The satellite command system switches power to the Rubidium units. In addition there is a precision 10 volt regulator in the control to supply the reference for the D/A converters.

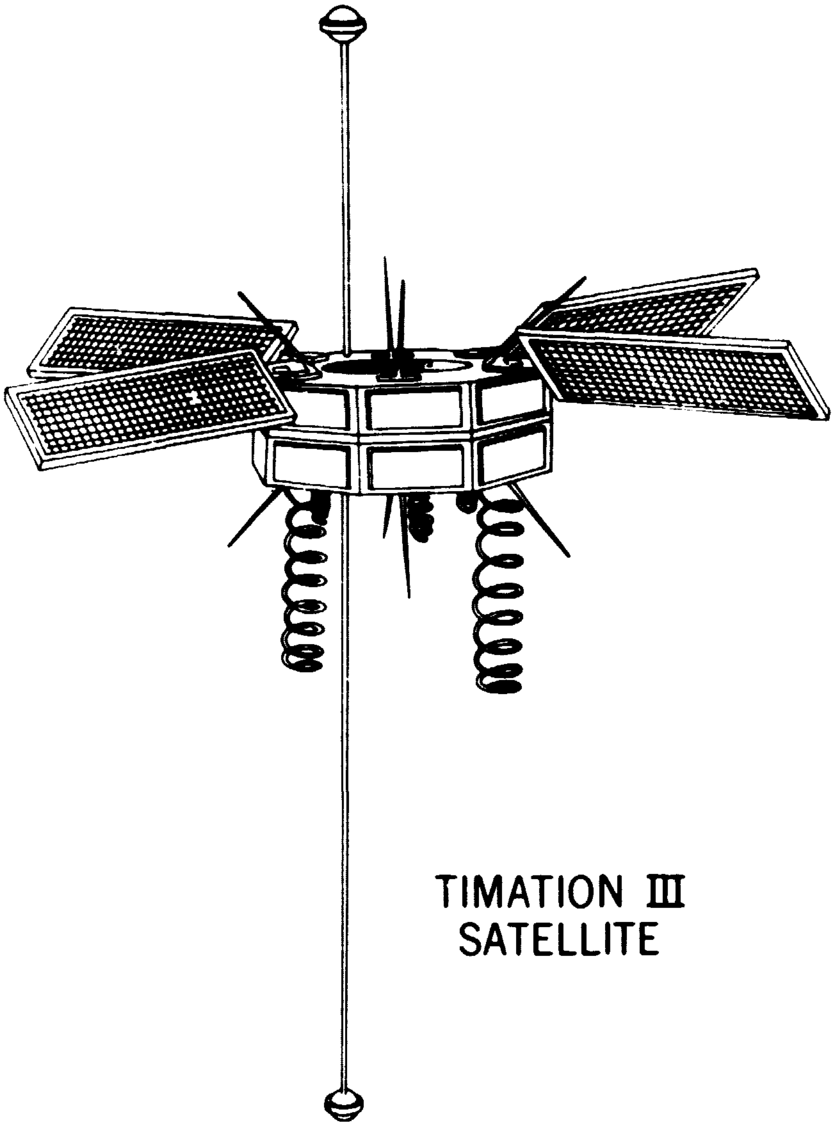


Figure 1. Navigation Technology Satellite I

Tuning the Digital Frequency Control is accomplished by sending a 14 bit serial word. This word can be loaded into one of three registers as determined by two of the bits. There is a 12 bit storage register to tune the Quartz crystal oscillator, a 10 bit storage register to fine tune the Rubidium Frequency Standard ("C" field adjust) and an 8 bit storage register to keep the Rubidium crystal oscillator within the lock limits of the control circuitry. The loading of the 14 bit word can be verified by digital telemetry before it is transferred to the appropriate storage register. There are also several provisions made to prevent spurious

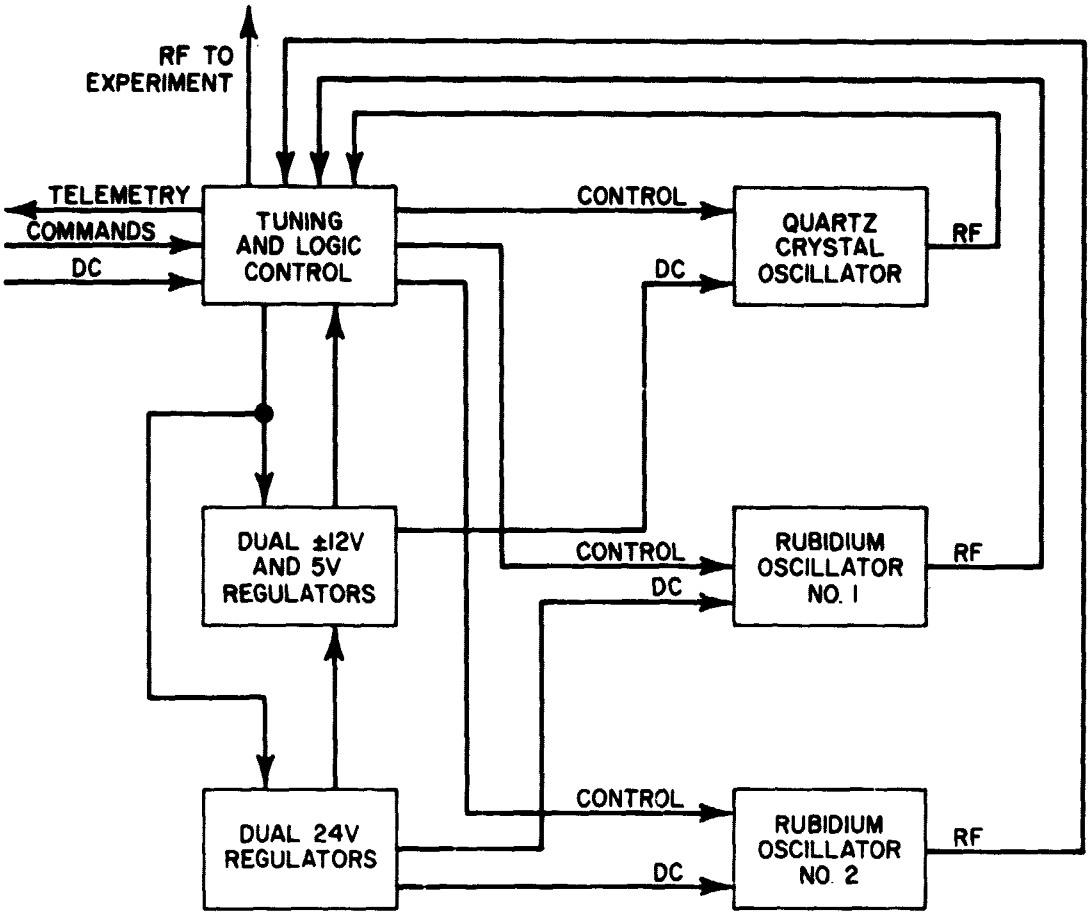
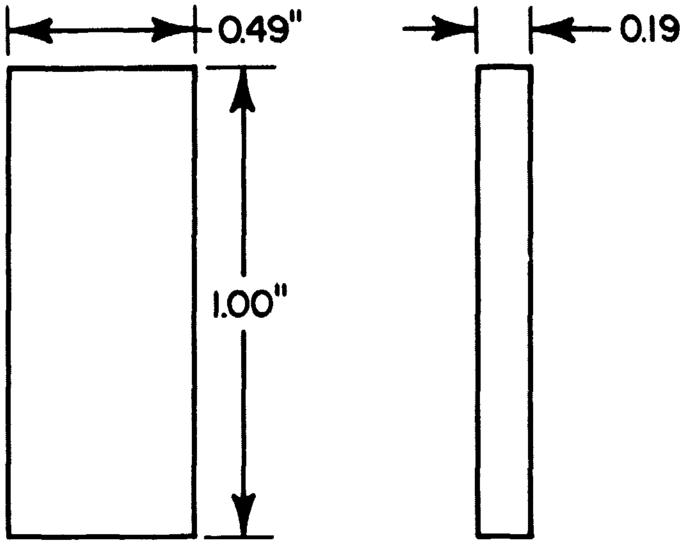


Figure 2. Frequency Standard System Block Diagram

signals from entering the Digital Frequency Control by disabling the input circuitry when it is not needed.

The D/A converter used for all three tuning commands is a 12 bit, thin film, hybrid low power module. Its specifications are shown in Figure 3. The pins have the same spacing as a dual in line integrated circuit package. It uses an external voltage reference which was mentioned earlier. Test of this voltage regulator showed a voltage change of about 0.7 mvolts from 10° to 40°C. This circuit was designed to be insensitive to supply voltage changes. In the satellite, the precision regulator will be temperature stabilized to within 200 millidegrees[7] and 200 millivolts supply voltage will be available. The 12 bit D/A converter will also be temperature stabilized to provide the necessary voltage stability to the Quartz oscillator varactor control. An operational amplifier circuit is used to convert the 0 to -2 ma D/A converter output to the 1 to 6 v output required by the



12 BIT DIGITAL TO ANALOG CONVERTER

POWER CONSUMPTION:	570 MW
LINEARITY:	± 1/2 LSB
TEMPERATURE RANGE:	- 25°C TO + 85°C
CONSTRUCTION:	HERMETICALLY SEALED DIP PACKAGE
INPUT:	TTL COMPATIBLE
OUTPUT:	0 TO -2 MA

Figure 3. D/A Converter Specification

oscillator. The output voltage of this D/A converter is expected to be stable to within one millivolt. The requirements for the D/A converters to be used to control the Rubidium units are not as stringent and therefore these units are not temperature stabilized. They do, however use the same precision voltage reference. The output voltage range of the 8 bit Rubidium crystal D/A converter is 0 to 5 v and the 10 bit Rubidium C field D/A converter output is 5 to 6.5 ma.

Provision has also been made to exercise the Rubidium units independently of the command system on the ground. In addition, several monitor points have been brought out to the satellite skin to allow performance monitoring during system checks. Figure 4 is a block diagram of the system.

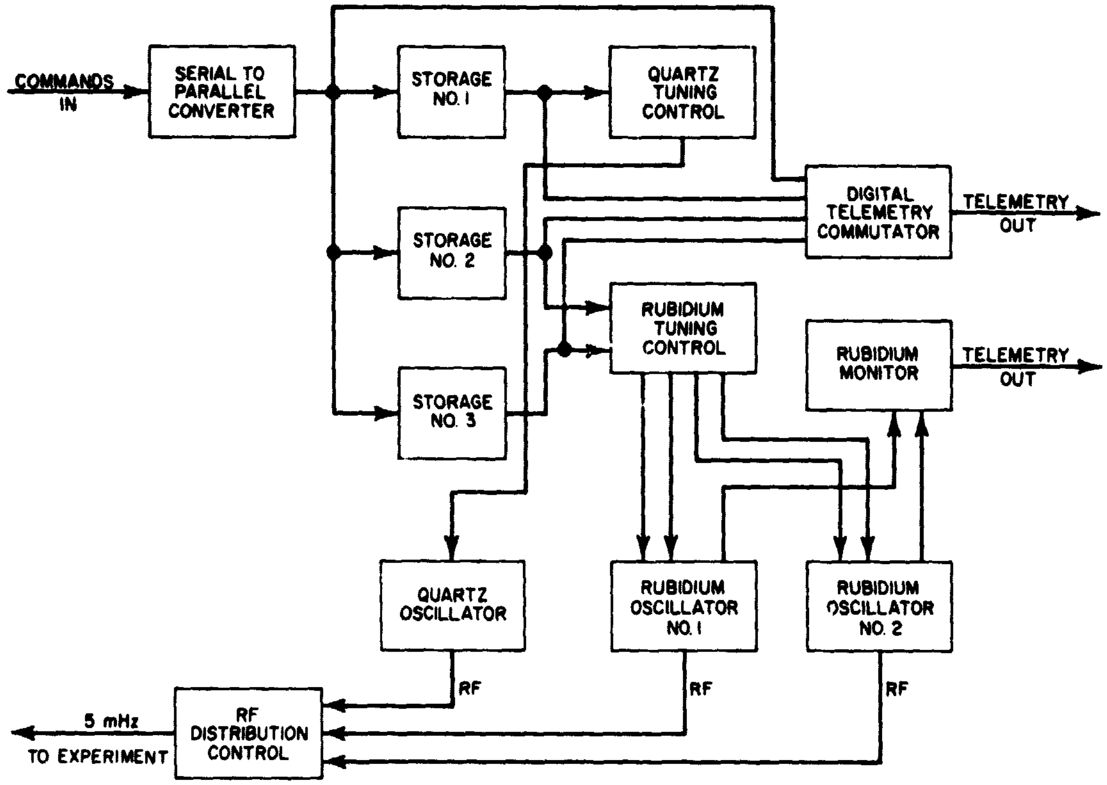


Figure 4. Logic and Tuning Control Block Diagram

Figure 5 is a photo of the prototype tuning the logic control box. This box will weigh 2-1/2 pounds and will contain most of the frequency control circuitry. Figure 6 shows the sizes and weights of the frequency standards and circuits.

Frequency Standards

The primary frequency standard for TIMATION III will be a 5 MHz quartz oscillator. A block diagram is shown in Figure 7. This is a 5th overtone, AT cut, double oven, oscillator that was built on contract for this satellite. This oscillator will have a natural aging rate of less than 1 pp 10^{12} per day or 2 pp 10^{9} over the planned 5 year lifetime. However, the calculated radiation induced frequency shift is -5 pp 10^{11} per day or 9 pp 10^{8} over 5 years, therefore the tuning range has been selected to be 1.5 pp 10^{7} with the smallest increment to be 2 to 4 pp 10^{11}, the range of values being due to the nonlinearity of the varactor response. This curve is shown in Figure 8. This oscillator, along with the precision voltage reference and the 12 bit D/A converter will be mounted on a thermal electric control device which will maintain the base plate temperature at 25°C ±0.1°C.

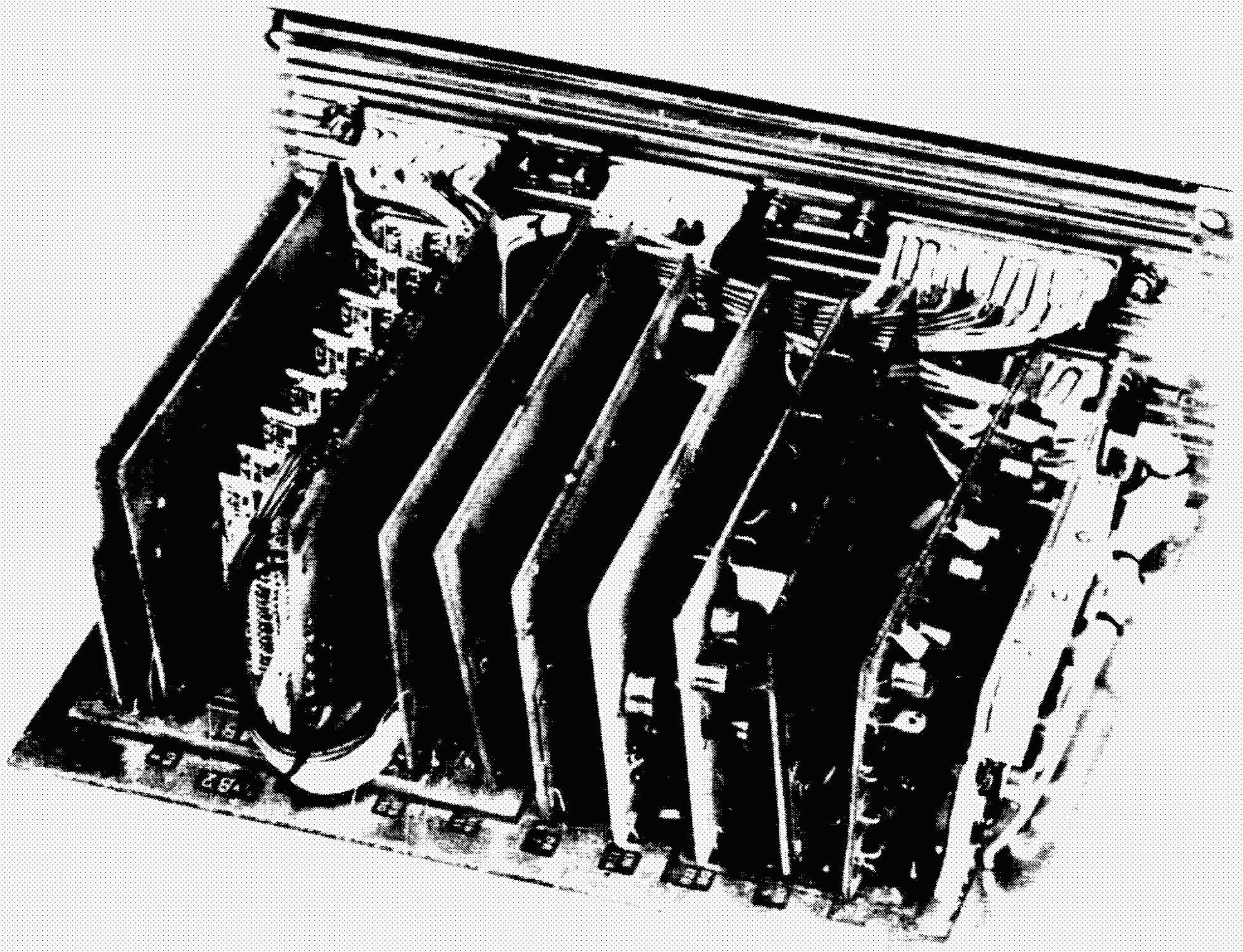


Figure 5. Logic and Tuning Control Photograph

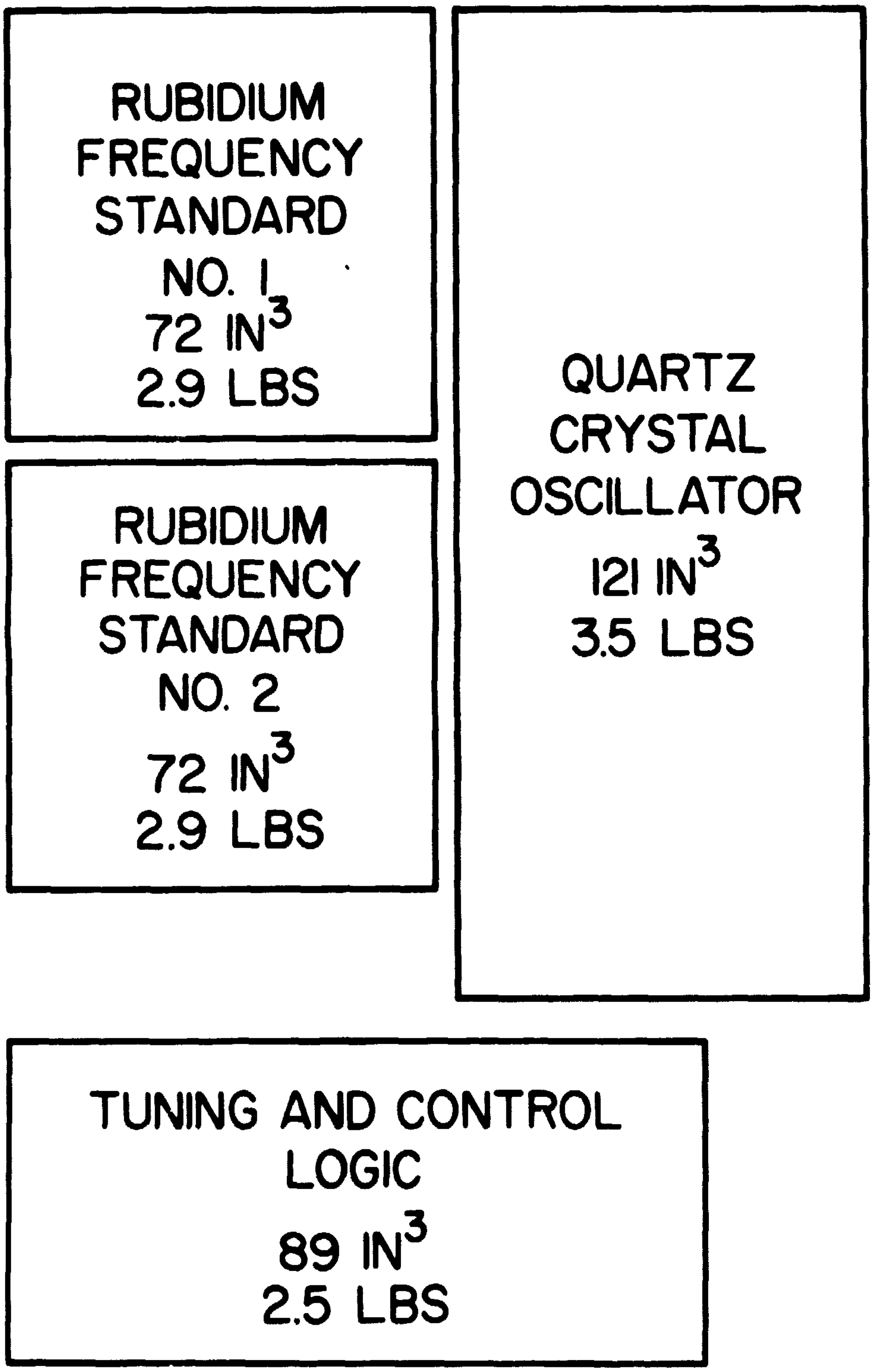


Figure 6. System Mechanical Details

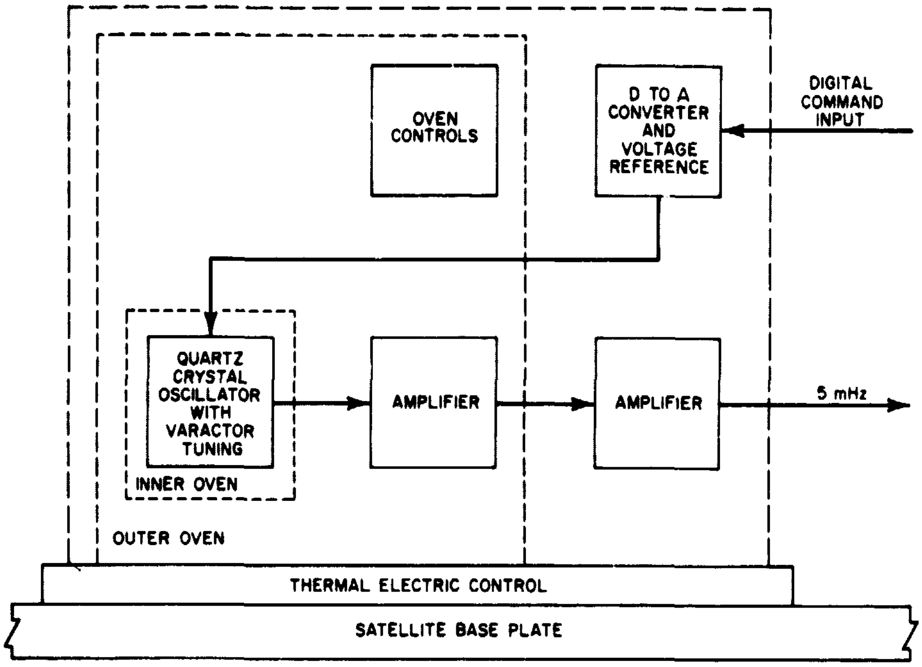


Figure 7. Quartz Oscillator Block Diagram

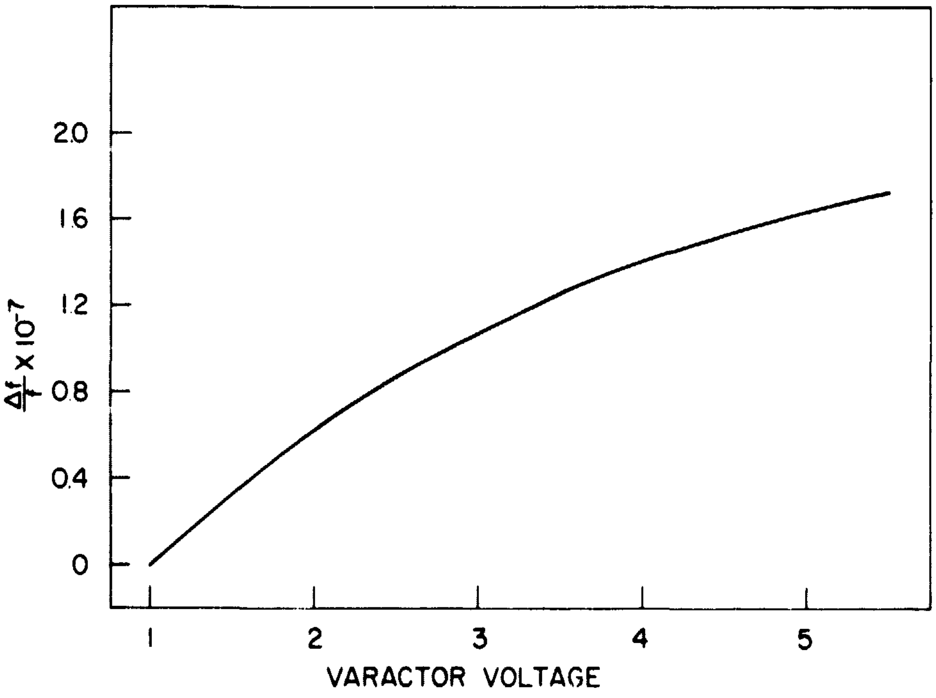


Figure 8. Quartz Tuning Curve

Two Rubidium Vapor frequency standards[8, 9] will also be flown to test their feasibility for space use. A block diagram is shown in Figure 9. Two units are to be flown for tests and reliability although only one can be turned on at any one time. These units are commercial units manufactured by Efratom Elektronik Gmbh, Munich Germany, which have been extensively used by NRL and modified for space use. Remote control of this unit is accomplished by controlling the Rb crystal oscillator, the C field current and monitoring the loop control voltage. The Rb crystal oscillator has two varactors, one for the loop control, and another to set the oscillator within the loop lock range. This oscillator has an expected aging rate of 3 pp 10^8 per month which is ten times the anticipated radiation effect. The 8 bit D/A converter will give this oscillator a range of 2 pp 10^6. By monitoring the Rubidium control voltage the oscillator may be periodically adjusted to keep it within the lock range of ±5 pp 10^7. The frequency output of the Rubidium unit can be adjusted by applying an external current changing the magnetic field around the resonance cell. A 10 bit D/A converter will give a range of 2 pp 10^9. The tuning curves are shown in Figure 10.

The dc power budget is shown in Figure 11. The tuning command power is shut off when not in use. The quartz system uses almost 3 watts and the rubidium system uses almost 13 watts.

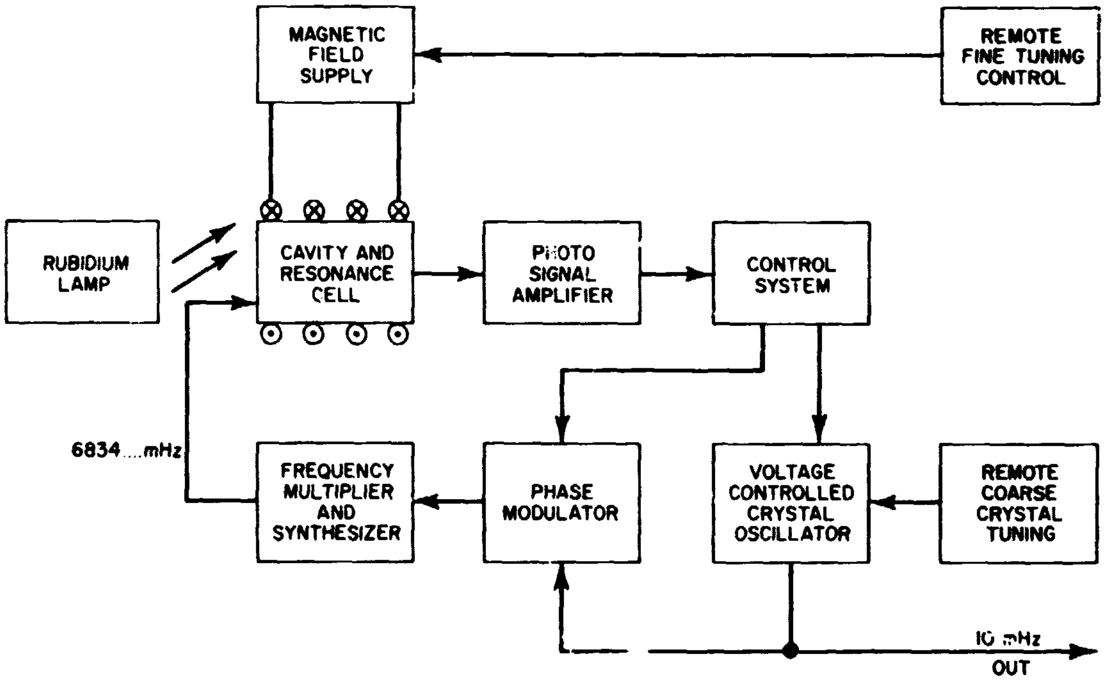


Figure 9. Rubidium Block Diagram

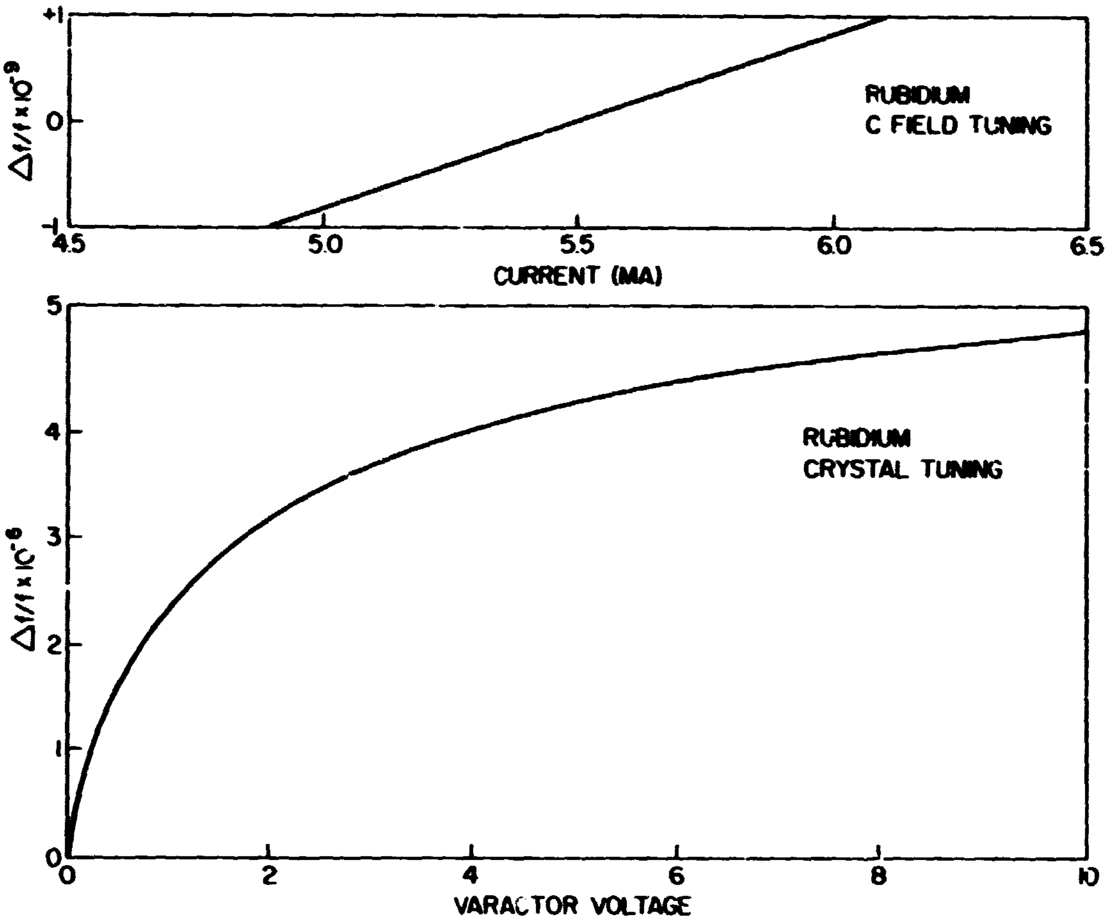


Figure 10. Rubidium Tuning Curves

DC POWER FOR
OSCILLATOR EXPERIMENT

	QUARTZ ON	RUBIDIUM AND QUARTZ ON
OSCILLATOR	1.8 W	12.8 W
TUNING COMMAND	0.3 W	0.5 W
CONTROL LOGIC	0.4 W	0.6 W
D/A CONVERSION	0.7 W	1.3 W
TOTAL FROM REGULATOR	3.2 W	15.2 W
TOTAL FROM BATTERY (90% EFF)	3.6 W	16.9 W

Figure 11. Dc Power Budget

CONCLUSION

The TIMATION III satellite frequency standard system will use a digital control system which will provide control of several frequency standards for spacecraft use for the purpose of testing new concepts and redundancy by the use of digital techniques, integrated circuitry and modern construction techniques. It will be a compact size, low weight, low power consumption device capable of being used with a variety of frequency standards.

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QUESTION AND ANSWER

MR. CHI:

Are there any questions?

(No response.)

MR. CHI:

According to the schedule, there will be a question period open to all the papers. Before I do that I should like to use the opportunity to restate the objective, which is to communicate the activities among the people working in different fields, from different agencies.

Now, I would like to open the session for questions of any paper which were presented during the day.

Please identify yourself, and also the paper or author to whom the question is addressed.

MR. MITCHELL:

I am Donald Mitchell. I am from the Kwajalein Missile Range, and I have a question on Mr. Matthews' paper.

Perhaps I misunderstood, but correct me if I am wrong. Did you state that you only made the evaluations of your delay measurements once every three months at your remote locations?

MR. MATTHEWS:

On the radar systems, yes, that is correct. On the telemetry system, it is as the mission is flown. The time bias is determined on an op-to-op basis. Does that answer your question?

MR. MITCHELL:

Yes, it does. Thank you.

MR. KRUTENAT:

Bob Krutenat, Naval Torpedo Station, for Mr. Nichols, the last speaker.

How severe were the vibration requirements for your rubidium standard, and how did they hold up?

MR. NICHOLS:

This was for an Atlas F launch, which is 13 GRMS overall and a fairly severe vibration. If our parts aren't very carefully mounted, we have trouble. We had problems with broken transistor leads and glass capacitors that short out on us and things of this sort.

The problem is mainly solved by making the printed circuit boards more rigid. The boards were originally mounted in the corners. We felt they were giving the parts a lot rougher ride than they should have.

We have now succeeded in getting past vibration, with four units, but it took a lot of work to get there.

MR. CHI:

As I can recall, you made four units, of which you had two, or did all four pass?

MR. NICHOLS:

In this program, we purchased a total of 10 units. We purchased four initially for prototype testing. We then purchased six more, of which we hope to get two good ones to fly. Of those six, we have taken the four best ones and got them through vibration testing. We will choose the flight one from one of these four.

MR. CHI:

Are all 10 modified?

MR. NICHOLS:

No, at this point only four are modified. The modification is so elaborate and complex that we only modified as many as we felt were necessary, and two of these have been destroyed in testing, taking them apart and putting them back together so many times. We now only have eight operational units left.

MR. CHI:

Dr. Kartaschoff.

DR. KARTASCHOFF:

Do you have some aging data over a long period of time on these rubidium cells? I tested one for 45 days and it remained within plus or minus one part in 10 to the 13th. So, it was much better than stated by the manufacturer.

MR. NICHOLS:

In general, we found the aging to be much better than the manufacturer by a factor of two. We have one on continuous aging for about seven months, and the aging has changed as the units have aged. It generally started off high and improved. I believe the units that we have aged the longest are somewhere around a part in 10 to the 12th per day, or less.

But I think more typical numbers are two to three parts in 10 to the 12th per day.

MR. WILCOX:

My name is Doug Wilcox, and I am from the Defense Mapping School at Fort Belvoir. I would like to ask Mr. Knowles a question on his paper, Applications of Radio Interferometry to Navigation.

Concerning this navigation system which uses quasars as a natural source, what would be the effect on it of a hostile environment, such as a war? How reliable would a quasar be for a navigation of a military vehicle?

MR. JOHNSON:

It would be as reliable as without a war. It is impossible to jam these sources, since they give out a noise spectrum over a very wide range. So, it would be impossible to jam them, so they are very good sources for that. The problem is that they are not very strong.

DR. WINKLER:

I would only have a comment, which does not apply to a single paper, but I would repeat my appeal that we should use a common language. I have found a couple of very strange numbers on some of the slides. For instance, the rubidium standard operating at 6,800 millihertz, or a crystal oscillator which requires 3.5 megawatts for its operation, or data which were given for Julian day "331", which indicates an event very early in human history.

Things like that, I think, again point to the need to be careful in our terminology and to use at least what we have already agreed on. Hopefully we will also agree on some additional terms which may be found useful.

MR. CHI:

Are there any more questions or comments?

MR. KAUFMANN:

I have a question for Mr. Matthews.

Have you considered the use of Loran-D now that it is available on the West Coast in the Vandenberg complex, as opposed to UHF?

MR. MATTHEWS:

Mr. John Schmid here is currently with SAMTEC engineering, and is currently implementing a Loran receiver at our Peno Point facility. Because our precision measurement lab is located at Vandenberg Air Force Base, there is not going to be a receiver located there. The Pemel lab will have the receiver, and they are like our quality control. They monitor our timing and they tell us when we are getting bad. They are immediately right there to repair the cesium if it is in trouble.

MR. KAUFMANN:

I was wondering about your remote locations.

MR. MATTHEWS:

At Kanton Island there were two Loran C receivers. I am not sure if there are any at Kaona Point; no.

MR. KAUFMANN:

I was really thinking about the Vandenberg complex where you transmit, as I understood, over UHF from your central time standard to other remote locations 100 miles or so away. Do you use Loran-C at those remote locations and at the Vandenberg complex?

MR. MATTHEWS:

No. We are using an IRIG-A time code, which we are transmitting on this 1750 megahertz frequency, at each of the 12 remote locations that we have receivers at. We are currently under implementation to put dual receivers in at our telemetry data center, our tracking and receive site at Oak Mountain, which is south of Vandenberg, and at our launch control facility for Minuteman.

At each of these locations, both on the dual receiver basis and on the single receiver basis, we have time code generators there which are phase locked to that incoming IRIG time code, and that provides us the synchronization with our range time.

MR. CHI:

Are there any more comments or questions?

(No response.)

MR. CHI:

Perhaps Dr. Winkler would use one minute or so to inform people how good is Loran-D, and the availability of receivers and so on.

DR. WINKLER:

Well, it is certainly as good as any Loran station for at least differential measurements. The signal can be received with regular Loran-C timing receivers. It gives a signal which you can receive all over California, and a considerable part of the other Western States.

In addition, we are publishing regularly now in our Series 4 bulletins, times of emissions, which are obtained by the Camp Roberts SATCOM terminal in direct synchronization back to the observatory. We are also benefiting from some additional monitoring which is reported back to us.

We hope eventually we are going to have two independent links back to the observatory.

Also, I think that as the number of users has increased, particularly within the Air Force and the Navy and other organizations, that it will be possible to increase the periods of operations.

We have had an increase recently, and maybe another one later on, as more users inform us and the Air Force of their needs.

So, I have a feeling that this is at least one useful system now in existence which from day to day is certainly as precise in its operation as the standard Loran, except there are some slight problems in regard to operator convenience, since the chains are still turning off during the night, or are only in operation during the daytime. The receiver will unlock, and the next day when the station comes back on, it does require a manual intervention to lock it back on. And there is some initial searching procedure on the part of the Loran operators which we are trying to improve. We are preparing some equipment, in cooperation with the Air Force, to assist in eliminating that searching procedure on the transmitter part.

I point this out, because it certainly is not yet completely comparable to the standard Loran as operated by the Coast Guard, which is a real fine operational system has made a remarkable record.

However, we do feel that anyone who keeps these few inconveniences in mind can get high precision timing service.

MR. MERRION:

Mr. Merrion (DMA). I would like to just ask you, are these stations permanently located here now? Are they going to be here for the next 10 or 15 years?

DR. WINKLER:

I think they are as permanent as anything we do nowadays, which cannot be predicted more than maybe a week in advance with real certainty.

It is certainly correct, and I have to tell you this, that these stations originally are contingency stations which may be cut off. However, the need for such a service is so great that I think I would recommend that anyone who can, get a Loran receiver and use it, until the signal disappears, and in the meantime we will see what in addition can be done.

We have some other things in preparation. We have hopes to be able sooner or later to improve the timing available from local television stations on the West Coast. Some development is underway.

We come back again to the question of reliability of service. I think we come back also to the fundamental principles in timing that we had better use what is available; and we had better have some redundancy in service and in our sources for timing — which is even more important. Some redundancy is indispensable in our operations.

For the foreseeable future, let's say a year or several years hopefully, I think the Loran D West Coast service has an excellent capability, and within that period of time other things will be developed.

I think we will hear about that tomorrow.

MR. MONTGOMERY (WSM Radio in Nashville):

We have been operating phase lock with the Bureau of Standards, WWVL, for some three or four years now, and if you have a receiver that will tune in 650, you can get this standard carrier there.

DR. WINKLER:

And a good program also.

MR. MONTGOMERY:

Right.

(Laughter.)

DR. KLEPCZYNSKI:

I just have one small comment to make in view of the energy crisis that is coming along.

Somebody mentioned in one of the talks earlier that the biggest problem they had in a remote area was power supply. I feel that perhaps in the future it might not only be in remote areas that we will have this problem.

MR. CHI:

Are there any more questions?

(No response.)

MR. CHI:

If not, I would like to turn the session over to the general chairman, Dr. Klepczynski, for the closing remarks.