PATH DELAY, ITS VARIATIONS, AND SOME IMPLICATIONS FOR THE FIELD USE OF PRECISE FREQUENCY STANDARDS

by

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Abstract

In order to assess the practical utility of high preformance frequency standards in field applications, the effect of the propagation medium must be taken into account.

After a brief summary of noise processes, a discussion of the performance of current frequency standards is given, together with an estimate of the relative cost, reliability, and necessary system support for each type.

Literature references on atmospheric physics are given to allow determinations of those limitations which the earth's atmosphere and ionosphere impose on the transfer of precise frequency and time. Formulae are presented to estimate the effects of changes in temperature, pressure, humidity, and frequency on the propagation path of electromagnetic waves. Current methods used to compute the path delay for HF, VLF, Loran-C and other precise frequency transmissions are given. Based on this material, we outline needs for future frequency control capabilities.

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DISCUSSION

DR. VESSOT: First, I would like to commend your physical intuition, or your physics, in your statement concerning the white phase noise of atmospheric and ionospheric measurements. Recent measurements made using the hydrogen maser at two sites, namely Haystack and Greenbank, using VLBI techniques on water vapor line noise sources at 22 gigahertz show, very definitely, white phase noise down to about 3 parts in 10^{13} at 100 seconds. I share your intuition in wondering how one could expect the ionosphere to "go away" logarithmically. It's a bit like the old saying "the sky is falling in."

Those are the good comments; now for the bad ones. First of all, the data reported by JPL go up to a million seconds which is on the order of ten days. I admit that you have had very bad luck with your masers, and I should also say that the ones that have been operated at NRL are probably very old. The third and fourth instruments that I made might have been the seventh and eighth that were ever made, and I commend the people who have been running them and who have kept them alive for so long. I suggest that another part of my institution, which is the Smithsonian, might be very interested in those instruments. I also accept any challenge you might issue to improve your data by either the slight refinement or the updating of the instrument you have, or perhaps to bring one to you that may be of a little bit more modern construction.

DR. WINKLER: I think these are very interesting (and promising) comments. However, my main concern is that, for operational use, machines are needed which can be operated without a Ph.D. and which can be relied upon to work with an average mean-time-between-failures of at least, for a clock, 5,000 hours. In fact, to come back to my previous comments, I think we make a fundamental mistake if we confuse serviceability concepts --mean-time-between-failures and so on. What we need are instruments which can be turned on and will keep working for five years at least, hopefully for ten. By that time, they should be so surpassed by the new technology that they can be safely thrown away or given to the Smithsonian Institution.

MR. PETERS: On the question of field operability of hydrogen masers, although we have not published enough data on these facts, out of four years and two months of operation of experimental masers we've got about four years, one month and two weeks. Furthermore, the down-time was due to experiments we wanted to make. One of our masers (NPI) has been operating in the field continuously since 1968 and has been moved all over the face of the earth without any malfunctions. These have been operated by station personnel. In fact, in two of our field installations, no service calls by the manufacturers were necessary. We have an integrated operating time in the field of about ten or twelve years. We do not have any data to support the view that our lifetime will exceed five years, only because these masers have not been operating more than four years since they were built. Extrapolations of their present performances indicate that this type of device will operate up to the extent of the mean time before failure of the electronic components. This, in turn, depends upon how much effort is put into quality control when producing such a device.

DR. WINKLER: Mr. Peters, this is very fine and I am glad to hear it. Would you please care to comment on my last chart where you see the main benefit of the hydrogen maser?

MR. PETERS: The other thing is we are auto-tuned on our hydrogen masers, as other people have done. With auto-tuning, you would never make a parallel between the gaseous processes, which are probably the predominant drift mechanisms in rubidium cells and a hydrogen maser. Certainly the position of the curves for future hydrogen masers ought to lie on the same chart. We must assume parallel rates of development and judge whether one type of standard or the other might be the more useful one in the future.

Another reason, of course, is that the economics of hydrogen masers are going to go way down if they are used widely in the future.

I'm afraid I didn't answer your question. That was the last chart. I think that that curve does represent NRL3 and 4 and later H-10 designs with which you certainly have had unfortunate experiences.

DR. WINKLER: I would not completely accept that, because I think the lowest points on this curve and also the left branch of it, have been taken from your publication. The dotted line, again, is one of which we know only a few points. Consider the physics of a passive frequency standard like the cesium, which is not subject to cavity pulling, which has a magnetic field factor 42 times less than that of hydrogen, and which observes the atom completely isolated in space, as compared to the physics of a standard imprisoned in a buffer box, where it is subject to 10^4 collisions per second. Would you think that the physics are so similar as to expect that these lines would be parallel, as Mr. Peters has suggested? I cannot imagine that. I think that is where our lines part.

MR. PETERS: I would like to comment,at least, on two aspects of that. One is, of course, the magnetic field dependance. You operate at about 50 milligauss. The actual variation with the field is much lower for the hydrogen maser, due to the fact that we operate in the field at one milligauss. Our net magnetic correction in all our operating standards, which are not degaussed from year to year, is 2 parts in 10^{12}. This is a very small effect in hydrogen masers, so the magnetic field problem is not really part of the present discussion. It can be measured with the ultimate precision just as you can with cesiums.

DR. WINKLER: Please do not interpret my remarks as putting down the hydrogen maser as a beautiful scientific instrument. My remarks are entirely regarding the immediate usefulness of these devices for applications in systems as we have discussed them here. This is the background of my remarks. I am not, at the momemt, concerned with the widespread use of very long base line radio interferometers to bring time to a submarine, or to navigate, or for similar exotic applications. They may be possible; they should be looked into, but right now the question is what should be developed with DOD money? I think that's the background of my consideration here, and the purpose of my discussion.

MR. PETERS: Yes. I hope my comments were based on physical facts and not on duty, particularly in referring to the magnetic field dependance. I think, to fully answer all of these questions and problems at such a time, one would really need to prepare a paper on the subject, to present another point of view.

DR. WINKLER: I think my paper, up to now, has been eminently successful because we have had more questions and comments than on any other.

MR. LIEBERMAN: I wonder how your last chart and the weighted chart on standards would be revised if we add the disciplined oscillators--the new ones--into your calculations. Would it clean up short-term stability and be a general addition to what you had there?

DR. WINKLER: I think it would be a very good idea to add to it. I do not have enough information; I think we should do that however. It will require some test results.

DR. RUEGER: I was involved a little bit more in the earlier days of the cesium standards until Hewlett-Packard gave it the engineering I think it needed. We had a lot more unreliability problems than you've been able to tell me about in the hydrogen masers. I, personally, feel that the hydrogen maser problem, or feature, that is going to be predominant in the future has to do with its absolute stability and the fact that it has high spectral purity. With the applications in which I am concerned, the spectral purity is of great concern, and is not available with the others yet.

DR. WINKLER: That is very remarkable. Can't you get the spectral purity by locking or following Dr. Cutler's recipe either, for instance, by locking a klystron to a harmonic of one of the crystal standards? What you are saying here is that you need both spectral purity and a carrier of extreme long-term stability.

DR. ALLEY: There have been recent developments in optical pumping of cesium which may lead to a cesium maser. This may, in the long run, have the same kind of short-term spectral purity that the hydrogen masers exhibit. They could be readily combined with beam devices to provide the long-term stability as well. This is a long way from realization, but there seems to be considerable promise there.

MR. PETERS: I think it is probably appropriate to make another comment on the other hydrogen device with which I have been working; that is, a hydrogen beam device. We haven't locked it on at this time; yet, we do have resonances, so we may have, perhaps, cesium masers and cesium beams; we have hydrogen masers, perhaps hydrogen beams.

DR. WINKLER: Mr. Chi, please.

MR. CHI: I agree with your analysis, however, you do admit that the analysis is time dependent in short-term stability in the term of five years or so.

DR. WINKLER: Of course. Also, I repeat what I said before. My presentation has had two purposes. First, to bring up a subject for consideration, to start some thought processes among ourselves here, as a community; and second, to provide some references which I will give in the minutes of the proceedings. Otherwise I have said, and your comment forces me to emphasize it even more, that much of what I said about the contributions--the short-term contributions of the atmosphere--is really not too well documented, in fact, it is largely conjecture. My point has been to bring out the main ideas on how one can hope to deal with these things in the systems conceptual way.

MR. CHI: However, when you make a comparison of the behavior or performance of different types of standards (I think in the figure of merit) you should probably also include the total investment per type of standard. Obviously the performance is proportionate to the amount of time as well as funds put in.

DR. WINKLER: You mean development funds should also be reflected. If you refer to the U.S. Government development funds, the cesium standards would come out extremely well, at least in this particular example which we are using, because it was my understanding that it was not developed under U. S. Government funding.

MR. CHI: I mean the total funds.

DR. WINKLER: Yes, Dr. Reder, don't you have some figures of how much money was actually put into some of these standards?

MR. CHI: I'll give you a guess before he gives you the total amount. I think if you add up the total costs of R&D, the crystal will have the highest amount of time and money put in, and cesium's the next, and the rubidium and hydrogen maser, in that order.

DR. WINKLER: Well, I think that is probably true.

DR. REDER: If we forget about some very unfortunate development contracts after Hewlett-Packard got into the act, I would say about six million dollars altogether. However, this includes the work on rubidium and the work on some other schemes; it is actually very difficult to separate, since the rubidium people benefited very much from the development of cesium.