THE NATIONAL RADIO ASTRONOMY OBSERVATORY
SOCORRO, NEW MEXICO
VERY LARGE ARRAY PROGRAM

VLA ELECTRONICS MEMORANDUM NO. 198

HYDROGEN MASER CLOCK TRIP REPORT AND PROCUREMENT RECOMENDATION FOR THE VLA AND THE PROPOSED VLBI SYSTEM

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1.0 INTRODUCTION

A fact finding trip was instituted the week of 8/4/80 with the purpose of comparing the current state of technology and production capability of the two current existing U.S. manufacturers of hydrogen maser clocks. Discussions were held with Bob Vessot of the Smithsonian Astrophysical Observatory, Vic Reinhardt of the NASA/Goddard Space Flight Center and Lauren Rueger of the Johns Hopkins Applied Physics Laboratory (the production facility for Goddard masers). In addition, other people associated with masers and their use were contacted. A schedule with names, speciality, addresses, and telephone numbers is given in the next section.

2.0 SCHEDULE

2.1 Monday 8/4/80 (Smithsonian)

Bob Vessot; Head of Smithsonian's Maser Clock Effort.
Address: Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138.
Telephone No. FTS 830-7276, Commercial (617) 495-7276

Eric Blomberg; Electronics Engineer working for Bob Vessot.
(No longer with S.A.O.)

Ed Mattison; Physicist working for Bob Vessot.
Address: Same as above.
Telephone No. FTS 830-7265, Commercial (617) 495-7265

2.2 Tuesday 8/5/80 (Haystack and Millstone)

Alan Rogers; Astronomer (built own maser receiver a number of years ago).
Address: Haystack Observatory, Off Route 40, Westford, MA 01886.
Telephone No. FTS 8-617-692-4764, Commercial (617) 692-4764

Len Hanson; Engineer (Timekeeper at Millstone Observatory).
Address: Millstone Observatory, Off Route 40, Westford, MA 01886.
Telephone No. ?

2.3 Wednesday 8/6/80 (Goddard)

Tom Clark; VLBI Astronomer
Address: NASA/Goddard Space Flight Center, Radio Astronomy Branch, Code 693, Greenbelt, MD 20771
Telephone No. FTS 344-5957, Commercial (301) 344-5957

Vic Reinhardt; Head of Goddard Maser Research and Development

Address; NASA/Goddard Space Flight Center, Code 814, Greenbelt, MD 20771.

Telephone No. FTS 344-5946, Commercial (301) 344-5946.

2.4 Thursday 8/7/80 (Johns Hopkins A.P.L., NRAO-CV)

Lauren J. Rueger; Head of Johns Hopkins APL Maser Production Facility for Goddard Masers.

Address: 4-326, The Johns Hopkins University, Applied Physics Laboratory, Johns Hopkins Road, Laurel, MD 20810

Telephone No. FTS ?, Commercial ?

Sandy Weinreb; NRAO-CV

2.5 Friday 8/8/80 (Green Bank)

Jim Moran; VLBI Astronomer

Address: Smithsonian Astrophysical Observatory, 60 Garden St., Cambridge, MA 02138

Telephone No. FTS 830-7477, Commercial (617) 495-7477

George Groves; NRAO (Green Bank Timekeeper)

Ken Kellerman; NRAO (Green Bank VLBI Astronomer)

3.0 HIGHLIGHTS OF VISITS

3.1 Smithsonian Astrophysical Observatory

Bob Vessot did not believe NRAO should undertake construction of the maser receiver as a cost saving measure. Some specialized technology such as low $^{1}/_{f}$ noise amplifiers and multipliers is involved if maximum performance is desired. Bob Vessot and his group have put a lot of work into the design of the receiver. His engineer is dependant on this effort. It appeared to me, from what I was able to see, (they did not want to go into details to protect their design) that the electronics package was a good design, with considerable care taken to insure reliability. Only professional technicians (no students) were used for assembly and it appeared to be of excellent quality. Two of these three technicians are NASA qualified. Considerable documentation with engineering change order control was utilized, although it was admitted that problems have occurred with changes and documentation. From what I saw, I believe their quality of documentation and fabrication to be equal to the best of the VLA effort.

The VLG-11 maser utilizes a 100 MHz voltage controlled crystal oscillator. The 1420 MHz preamp is an Avantek 3.5 dB noise figure 22 dB gain amplifier prociding a total system noise figure of 6 dB. A two-time constant phase locked loop (50 Hz BW normal, 5 KHz at pull-in) is used to phaselock the 100 MHz VCXO. An optimum loop bandwidth has not been investigated. (The VLG-10 ran at 20 Hz loop bandwidth.)) Both VLG-10 and VLG-11 masers have a 5 MHz E. C. L. sinewave output filtered and buffered. Harmonic content is down about -26 dB.

Spares for electronics modules are not kept because of lack of electronics failures.

Eric Blomberg and Bob Vessot will not hand over their receiver drawings for NRAO duplication. Therefore NRAO would have to engage in an original effort.

i) NRAO IN-HOUSE DESIGN OF MASER ELECTRONICS

To duplicate Bob Vessot's effort with the electronics package I believe would take one to two man-years of a fulltime R.F. design engineer, one R.F design technician, and one high quality draftsman, for a prototype capable of duplication for VLBI. Doubling salaries for overhead this would result in a manpower development cost of between $100,000 and $200,000. Ongoing design changes and assembly would have to be added to this for 10 more units, but will not be included here. I believe the cost of the parts for the electronics package (similar to Vessot's) would be less than the previously mentioned $20,000, possibly $10,000.

Therefore, I believe the total development cost would be between $110,000 and $210,000, for a simple receiver (with no remote monitor and control interfacing). This latter would probably require one additional man-year of a digital design technician at $30,000 with overhead, and $5,000 in hardware. Some additional computer programming assistance for diagnostics should also be added to this. If a common analog/digital communications system is to be used for each site similar to the VLA DCS system, the Smithsonian Maser could be directly interfaced. (A monitor jack is already provided. Control of circuit breaker lines, etc. could be added for the turn on sequence.)

ii) PERFORMANCE OF SMITHSONIAN MASER

Bob Vessot uses a "cervit" low thermal expansion glass-ceramic material that is very stable for his cavities. A 1 to 1 length to diameter ratio has the advantages of mechanical stability and smaller size. The cavity is varactor tuned.

Bob Vessot believes the VLG-11 series masers to have a stability on the order of 6 parts in 10^{-16} in 3000 seconds. A VLG-11 maser has not as yet been compared directly with a Johns Hopkins APL maser. The VLG-11 is 10 times less susceptable to changes in nearby magnetic flux than the VLG-10 series.

iii) PRESENT PROBLEMS AND FAILURE MODES

The ion pump is being replaced with an absorption pump and should result in better reliability than in past units. The transistor oscillator used for plasma ignition has a problem with spurious oscillations and requires careful tuning. Cavity bedding down (required before use) takes 6 months to occur. The VLG-11 series is being redesigned with radical changes in the electronics package, especially elimination of connectors as much as possible. They had a problem with SMA connector plating flaking.

iv) FUTURE DEVELOPMENT PLANS

The Smithsonian is planning to abandon the ion pump and go to an absorption pump. New magnetic shields are going to be implemented. Future units will probably incorporate more use of titanium since it is stronger and has better thermal resistance. Less "o" rings will be used and the unit will be made easier to duplicate and repair. Most of these improvements are cost effective actions. Bob Vessot guessed at 2-3 parts in 10^{-16} in 10^{4} seconds for future masers.

A cryogenics oscillator is at best a good flywheel for a maser. Stanford's test of their cryogenic oscillator showed it to be no better than a maser for periods better than 1000 seconds.

Bob Vessot is researching cold masers with predicted stabilities in the 10^{-17} area, and has built passive masers.

3.2 Haystack

Alan Rogers built his own maser receiver in 1973 using a commercial synthesizer. He has had no reliability problems with his receiver. He used a 5 MHz VCXO with many multipliers and band pass filters. He used a loop bandwidth of 1.7 radians/sec. There seemed to be only notes and no formal documentation.

Alan Rogers recommends that we do not build our own receiver.

3.3 Millstone

Len Hanson gave a demonstration of their Loran C set-up.

3.4 NASA/Goddard Space Flight Center

Tom Clark (A VLBI Geodesy Astronomer) introduced me to Vic Reinhardt, head of Goddard's Maser Research and Development Facility). Tom had no complaints concerning the Goddard Maser and said that many of its features were user specified. Tom and Vic both agreed that it would be possible for NRAO to purchase the Goddard masers, if desired. An appointment was set up for the next day with Lauren Rueger of Johns Hopkins Applied Physics Laboratory, the production facility for Goddard designed masers.

Vic Reinhardt presented a history of maser technology to myself and two visitors from JPL.

i) <u>Description of Goddard Masers</u>

The "NR" masers (based on the Harry Peters' "NX" maser) is a production model with complete fabrication documentation. In order to free Vic Reinhardt to conduct research into maser improvements, Johns Hopkins Applied Physics Laboratory was set up as a seperate production facility under Lauren Rueger. The NR masers use a 2 to 1 length-to-diameter ratio cavity to minimize the effect of the end plates. Aluminum is used for the cavity material which eliminates the "seating" problem seen in the Smithsonian masers. The cavity is thermally tuned. Goddard/Johns Hopkins APL will not sell their maser physics package as a seperate entity. The maser can be "autotuned" through shifting the magnetic field and measuring the shift in maser frequency. Since the maser is thermally tuned this process takes several days. The maser has an internal AC power supply as well as batteries which allow fully hot operation for 3 days. An external 24 VDC source can also be utilized. The Goddard maser is much taller and heavier than the Smithsonian maser but is built to be shipped without an external container or pallat. Fork lift holes are built into the bottom of the rack. An F.A.A. approved hydrogen bottle and NASA certified safe battery container with sealed batteries permit air shipment. The Goddard phase detector gives short pulses to their integration capacitor making it easier to filter. Vic Reinhardt called it a "charge, discharge" phase detector. The loop bandwidth is several hundred hertz.

Three RS-232 interface connectors are provided for remote control and sensing, via a telephone line modem. Extensive monitoring permits easy diagnosis of defects.

Many of the features of the Goddard maser were user specified. The maser was designed as a completely self-contained unit. The NR-4 maser is fully documented with the exception of a service manual.

ii) Performance of Goddard Masers

Vic Reinhardt admits that Bob Vessot has better short term stability, due to higher $^1/_f$ noise in the Goddard electronics system, however, stability at longer sampling times should be comparable. Vic Reinhardt claims 1 part in 10^{-15} stability was achieved with NR-1. Two masers could be autotuned together to provide 1 part in 10^{-14} indefinately.

iii) Goddard Research Plans

In the past, Vic Reinhardt has been hindered with the NR production series. With Johns Hopkins APL taking over the production effort, several ideas on improvement of both the physics and electronics package will be investigated. Goddard is also investigating the use of an absorbtion pump rather than an ion pump for an improvement in reliability.

3.5 Johns Hopkins Applied Physics Laboratory

i) Addtional Goddard Maser Information

Lauren Rueger said that the NR maser internal clock and microprocessor can determine the exact period of downtime due to a failure. The NR maser microprocessor has an independently adjustable delay to the 1 ns level. Software could be generated in the internal microprocessor to readout difference from a Loran C receiver or even lock onto it. The synthesizer automatically compensates for a 1 part in 10^{-16} frequency change per 1 meter of altitude change.

He stated that a stability of 2×10^{-15} in 1,000 seconds would be typical. This could not be guaranteed. A service contract could be initiated (including remote monitoring of maser parameters) at 10% of maser cost/year. A per-problem basis for service would be a less expensive alternative. A quotation on a single unit was requested. (A quotation of $344,500 for 1 unit was recently received from Charles Blackburn of Johns Hopkins APL. This assumed NRAO funding would be available in December, 1980. This price is lower than normal since 4 other masers will be built during 1981. Therefore a quantity of 10 price would be the same.)

3.6 Greenbank

Reported to Ken Kellerman on maser trip.

4.0 CONCLUSION

I do not feel qualified to make a decision concerning which maser is "best". Two totally different design concepts result in different problems and advantages.

In trying to compare technical aspects, it became clear that a once only discussion with both parties did not suffice, especially since many of the design concepts are controversial. I feel the best thing that could be done for the country at the present time would be to eliminate the presidential debates and have a one on one debate between Bob Vessot and Vic Reinhardt. But this is unlikely to happen.

A "shoot out" between Bob Vessot's VLG-11 and Vic Reinhardt's NR-4 masers is going to be held this year at JPL's maser test facility. The tests will take 1 year to complete and may provide a useful comparison.

During the trip copies of a number of technical articles and publications concerning masers and time standards and measurement in general were obtained. A bibliography of these publications is given. The articles in NASA Conference Publication No. CP2115 are the most recent concerning maser performance. However, I can conclude from this trip that building the electronics package for a Bob Vessot physics package would be a bad idea for a number of reasons.

First the performance could not be guaranteed or even easily checked. The only way that the performance could be accurately checked would be by shipment to the Jet Propulsion Laboratory Maser Test Facility for an extended period of time. This would be impractical, and is not usually done with masers built in this way. Nancy Vandenberg (Phoenix Corporation), a VLBI astronomer under contract to Tom Clark has noted that VLBI techniques have improved to the point where instabilities are being detected which appear due to the maser clocks involved.

Second, maser receivers require special considerations not usually encountered by designers, in particular low $^1/_f$ noise amplifiers and multipliers. It is widely believed within NRAO that $^1/_f$ noise (near D.C.) in an amplifier will not occur in the microwave region unless intermodulation occurs. When Vic Reinhardt questioned the use of GaAsFet preamplifiers because of possible $^1/_f$ noise problems, I was told by a leading NRAO engineer, "I wouldn't buy a maser from that guy."

In a discussion with Donald Halford of NBS, the following information was related concerning this problem. First, $^1/_f$ phase noise will appear on microwave amplifiers regardless of intermodulation or class of operation. It is not due to upconversion. The $^1/_f$ am noise sidebands on a microwave carrier are much less than the $^1/_f$ phase noise sidebands. This would not be the case if $^1/_f$ phase noise on a microwave carrier were due to intermodulation. Also, phase flicker noise is the same for any class of operation. If it were due to intermodulation it would be worse for Class C than Class A, for example. This was first published in an article by Donald Halford, A.E. Wainwright, and James A. Barnes, entitled "Flicker Noise of Phase in R.F. Amplifiers and Frequency Multipliers: Characterization, Cause, and Cure" which appeared in the Symposium on Frequency Control, 1968. FLUKE has long utilized these techniques in their frequency synthesizers. Oscilloquartz also uses these techniques in their precision crystal oscillators. Hughes' engineers as well as JPL engineers working on precision radiometry have encountered this problem. In the words of the NRAO engineer, "I would not buy ..." an electronics package "... from that guy". While much background technology still exists within NRAO, other unforseen problems could degrade performance. References relating to this problem are given in the bibliography (Ref. 20 thru 24).

Third, the deliberate decline in NRAO engineering manpower may make a project like this either impossible or dangerous.

Fourth, Bob Vessot is extremely reluctant to sell his physics package seperately. This could generate some political friction which would be undesirable for NRAO.

Fifth, if a performance problem arises at a remote site that was difficult to diagnose as a physics or electronics fault, political friction could inhibit repair.

Sixth, the cost of development of a reliable, high performance and reproduciable electronics package would probably not make it cost effective for a few units. For 10 units, it would be. However, the funding could not be guaranteed and would probably be spread out over many years anyway.

Seventh, coordination of physics package delivery and electronics package completion and integration could produce delays in scheduling.

Eighth, vendor delays in delivery, prevalent in the electronics market today, could inhibit design and prototype completion.

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