NASA HYDROGEN MASER ACCURACY AND STABILITY IN RELATION TO WORLD STANDARDS

Harry E. Peters
Goddard Space Flight Center

Donald B. Percival *
U.S. Naval Observatory

ABSTRACT

Frequency comparisons were made among five NASA hydrogen masers in 1969 and again in 1972 to a precision of one part in 10^{13}. Frequency comparisons were also made between these masers and the cesium-beam ensembles of several international standards laboratories. The hydrogen maser frequency stabilities as related to IAT were comparable to the frequency stabilities of individual time scales with respect to IAT. The relative frequency variations among the NASA masers, measured after the three-year interval, were 2 ± 2 parts in 10^{13}. Thus time scales based on hydrogen masers would have excellent long-term stability and uniformity.

I. INTRODUCTION

Atomic hydrogen maser frequency standards, developed at Goddard Space Flight Center (GSFC) for field applications, have been used for several years at NASA tracking stations and other locations around the world.[1] This paper reports the results of measurements of accuracy, reproducibility, and long term stability of these masers. The results were acquired by comparing the masers with one another and with the time scales of several national laboratories which contributed to the international time scale (IAT) maintained by the Bureau International de l'Heure (BIH).[2]

Figure 1 illustrates the intercomparisons described. The five hydrogen masers to the left were designed at GSFC during 1966–1969. NX-1 was a fully operational experimental hydrogen maser which tested several design concepts; these were later incorporated into four field-operable prototype hydrogen masers (NP-1, NP-2, NP-3, and NP-4). NX-1 has operated since September 1967, as a basic frequency standard. The prototype hydrogen masers have operated almost continuously since their completions in 1968 and early 1969.

During construction and testing of the prototype hydrogen masers, measurements were made on all factors which affect their basic accuracy capability. In addition, careful intercomparisons determined the frequency relationships between them. Due to worldwide deployment for experimental applications since August 1969, only sporadic and inexact comparisons of the relative frequencies of the hydrogen masers were possible.

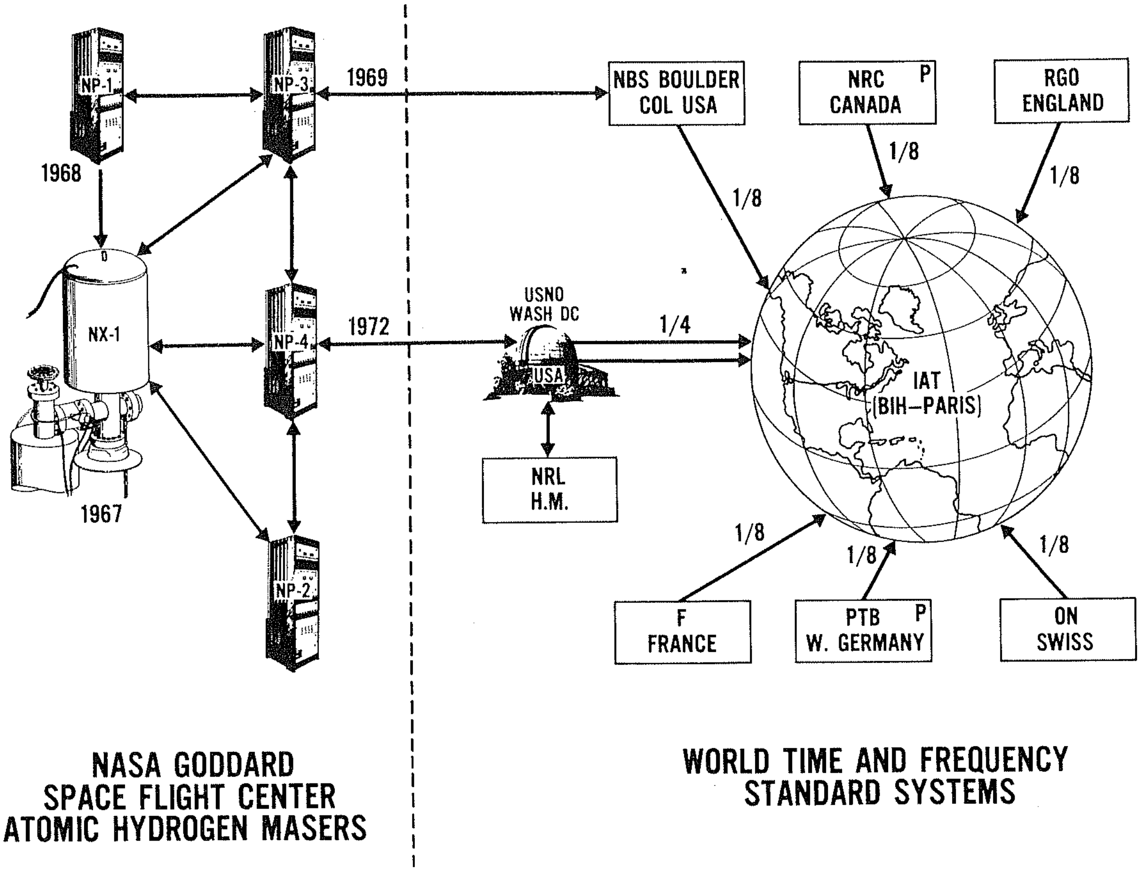

Figure 1. NASA hydrogen maser accuracy and stability measurement system.

In 1972 however, three of the prototypes were at GSFC simultaneously; precise frequency measurements were made among them and the NX-1 hydrogen maser. Combined with the 1968–1969 frequency measurements, these data allowed the determination of relative frequency differences, long term stability, and reproducibility of the four hydrogen masers over a three year interval. In addition, the remaining prototype maser, NP-3, which was at the NASA Apollo tracking station at Goldstone, California during 1972, was compared in frequency to the other masers, but it was compared with much less precision, using VLF, traveling clocks, and Loran-C.

Frequency measurements were also made between some of the NASA masers and various time scales.[3,4] For a three month period from late November 1969, to February 1970, NP-3 was compared at the National Bureau of Standards (NBS) in Boulder, Colorado with the NBS six clock ensemble. Some previously unpublished results of this comparison are given in this report.[5,6]

During 1972, through a collaboration of the United States Naval Observatory (USNO) and GSFC, the NP-4 maser was compared at the USNO for eight months with the USNO 16-

clock cesium ensemble. Simultaneously, NP-4's frequency was compared to the BIH's IAT time scale by using the USNO time scale as a link comparison. In turn, the BIH time scale provided a link to relate the frequency of the NP-4 maser to all the time standards laboratories associated with the BIH.[8,9] (See Figure 1.)

All laboratories contributing to the BIH time scale used a minimum of three Hewlett-Packard cesium-beam standards, which were maintained under good laboratory conditions. Under the weighting scheme used by the BIH to calculate IAT during 1972, the USNO time scale was given a weight of two, while the other six time scales were given a weight of unity. In addition, two laboratories (National Research Council of Canada, Ottawa, Canada, and Physikalisch-Technische Bundesanstalt, Braunschweig, West Germany) operated primary cesium beam frequency standards during 1972.

Besides its cesium-beam standards, the USNO operated a Varian H-10 hydrogen maser during part of 1972, as an interpolation oscillator to analyze frequency variations among cesium clocks. A microwave link between the USNO and the Naval Research Laboratory (NRL) gave the USNO access to two additional early Varian H-10 masers maintained by NRL.[10]

II. MEASUREMENTS RELATIVE TO STANDARDS LABORATORIES

Figure 2 gives the results of the 1972 frequency measurement between the NP-4 hydrogen maser and A.1 (USNO) (which is labelled USNO (MEAN) on the graph). A.1 (USNO) is the independent, uncoordinated, local atomic time scale derived by the USNO. While the net change in frequency between NP-4 and A.1 (USNO) was close to zero for the total period, there were clearly defined deviations from the average frequency of up to three parts in 10^{13}.

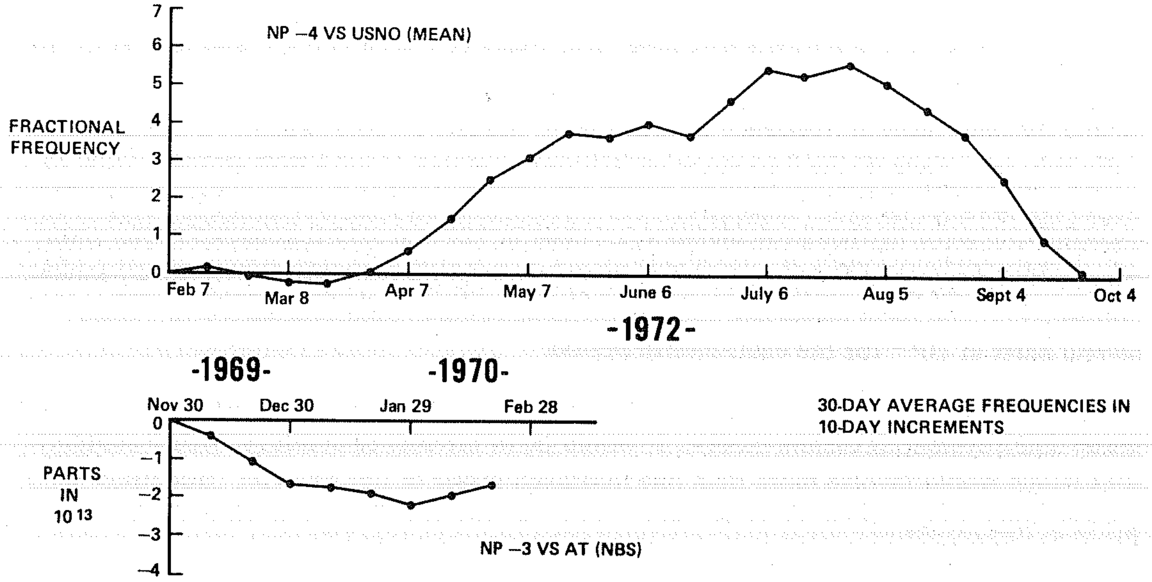

Figure 2. Frequency comparisons–NP masers versus U.S. standards labs.

Figure 2 also shows the results of the three-month frequency measurement between the NP-3 hydrogen maser and the six-clock NBS cesium ensemble in 1969–1970. An Allan variance analysis for 20-day sampling time gave a relative fractional frequency stability of seven parts in 10^{14}. The internal estimate of the variation in the NBS time scale was 4.5 parts in 10^{14}.

At both the USNO and NBS, the NASA masers operated in an average air-conditioned environment. The cavities of the masers were automatically tuned continuously with respect to a good crystal oscillator; for this mode of operation the automatic tuning system should limit cavity-related frequency excursions to less than one part in 10^{13}.[1] The variation of NP-4 with respect to A.1 (USNO) was approximately three times that expected, due to cavity-related frequency changes.

As discussed above, the algorithm used to compute A.1 (USNO) was designed to generate as uniform a time scale as possible. A.1 (USNO) has been evaluated from internal considerations to be stable to a few parts in 10^{14} for measurement periods from 10^6 to 3.10^7 seconds. However, estimation of frequency stability from internal consistency alone would be too optimistic if there were some unknown frequency shifts which were common to most cesium standards in an ensemble.[7] One effort to evaluate the stability of A.1 (USNO) against external standards has been made by B. Guinot and M. Granveaud.[9] Compared to IAT, A.1 (USNO) was found to have a stability of 0.6 to 1.3 parts in 10^{13} for averaging times of 60 days. (IAT, however, was not truly external to A.1 (USNO) since 25% of IAT was derived from the USNO time scale.) If this stability estimate were valid for the 240 day period in which A.1 (USNO) and NP-4 were compared, then the variation of A.1 (USNO) with respect to NP-4 was approximately three times that expected.

That time scales based on cesium ensembles do vary with magnitudes greater than expected from internal estimates of stability may be seen from Figures 3 and 4. Here the frequency variations of NP-4 and the contributors to the IAT time scale are plotted against IAT. (While the deviations in frequency between NP-4 and A.1 (USNO) shown in Figure 2 were definitely real, some of the frequency variations in Figures 3 and 4 were probably due to poor reception of LORAN-C signals, which were used to link the various time scales. This coordination error has been calculated as ± 1 part in 10^{13} on a 30 day basis.[9]) The variation of NP-4 against IAT was comparable to the variations of the contributing time scales against IAT. The NP-4 maser and the independent cesium ensembles agreed to within several parts in 10^{13} for the eight-month period.

Thus there was no clear, unambiguous conclusion as to the relative stabilities of a hydrogen maser and a system of cesium clocks. It would be of interest to conduct further comparisons which would involve more than one hydrogen maser of the NP type. Hopefully such comparisons would provide further data to evaluate the stability properties of hydrogen masers and cesium clock ensembles.

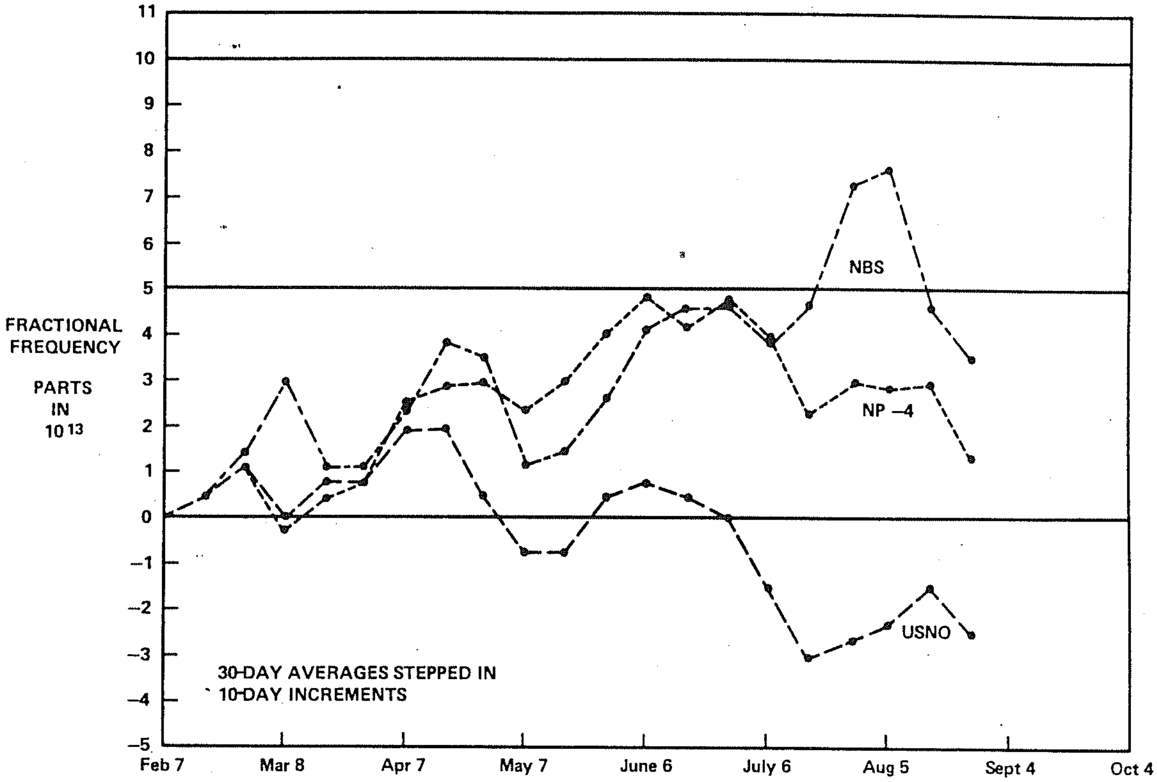

Figure 3. USNO, NBS and NP-4 maser frequency versus IAT.

III. MEASUREMENTS BETWEEN MASERS

Figure 5 shows frequency comparisons of the NASA prototype masers against the NX-1 maser in 1969 and 1972. The data have been corrected for second order doppler shift (with an error estimate of ±.0004 Hz), magnetic field measurement (±.0000013 Hz). and wall shift (± .0024 Hz). The errors associated with cavity tuning and the measurement technique were no greater than ± .00014 Hz. Since NP-3 was in Goldstone, California and was compared via traveling clock, VLF, and LORAN-C, there was an additional measurement error estimated at ± .0007 Hz.

Table 1 gives the 1972 absolute frequency of all of the NASA masers with respect to IAT. These values were referred to the 1972 NP-4 measurement reported previously.[8,9] The error estimate given for the average value of the absolute frequencies was that attributable to a single hydrogen maser since the major uncertainty, the wall shift, was a common systematic error. Table 1 includes a new value for the wall shift temperature coefficient associated with the hydrogen masers. The cavity temperature of NP-2 and NP-4 were lowered by 17°C. The resulting changes in the frequencies of NP-2 and NP-4 indicated that the previous value for the wall shift temperature coefficient was in error.* Because of this temperature change NP-2 and NP-4 in Figure 5 should only be compared to one another, and NP-1, NP-3, and NX-1 should only be compared to one another, in order to estimate the long term performance of the NASA masers.

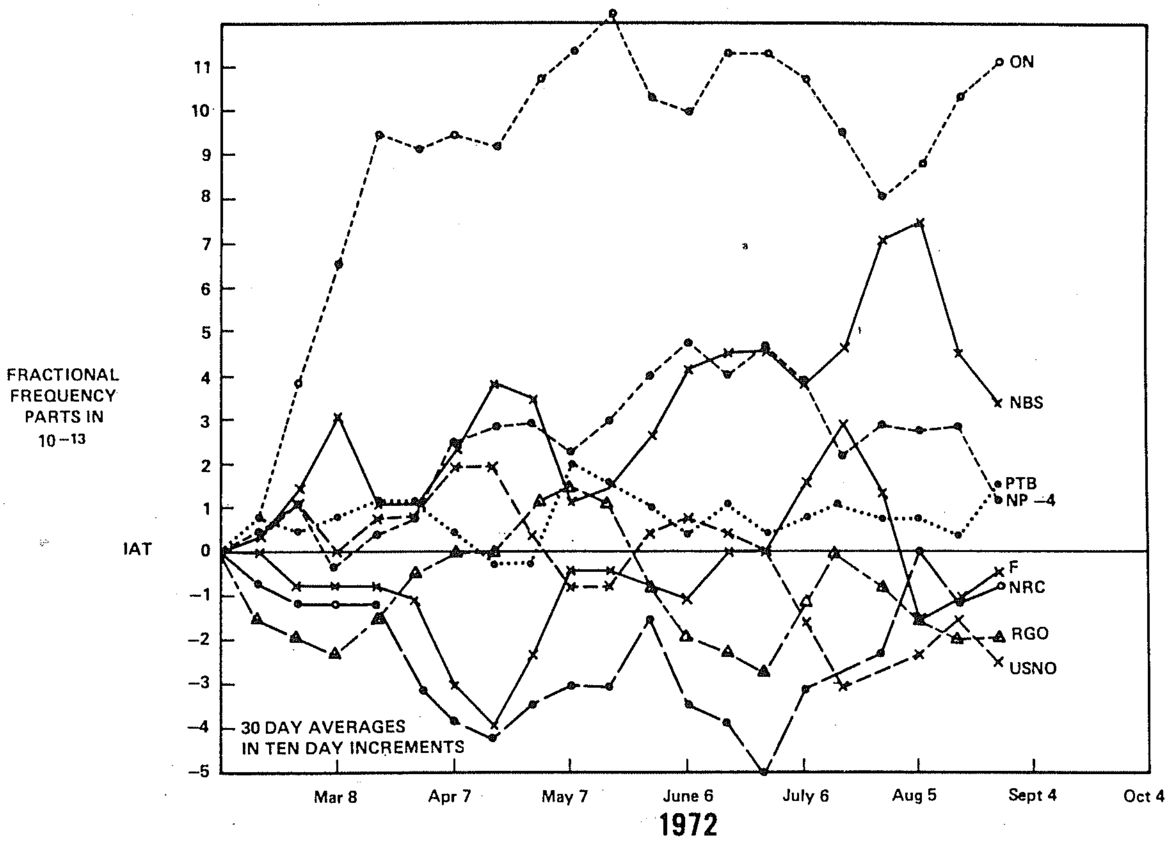

Figure 4. Frequency comparisons—International Standards Labs and NP-4 H-maser versus IAT.

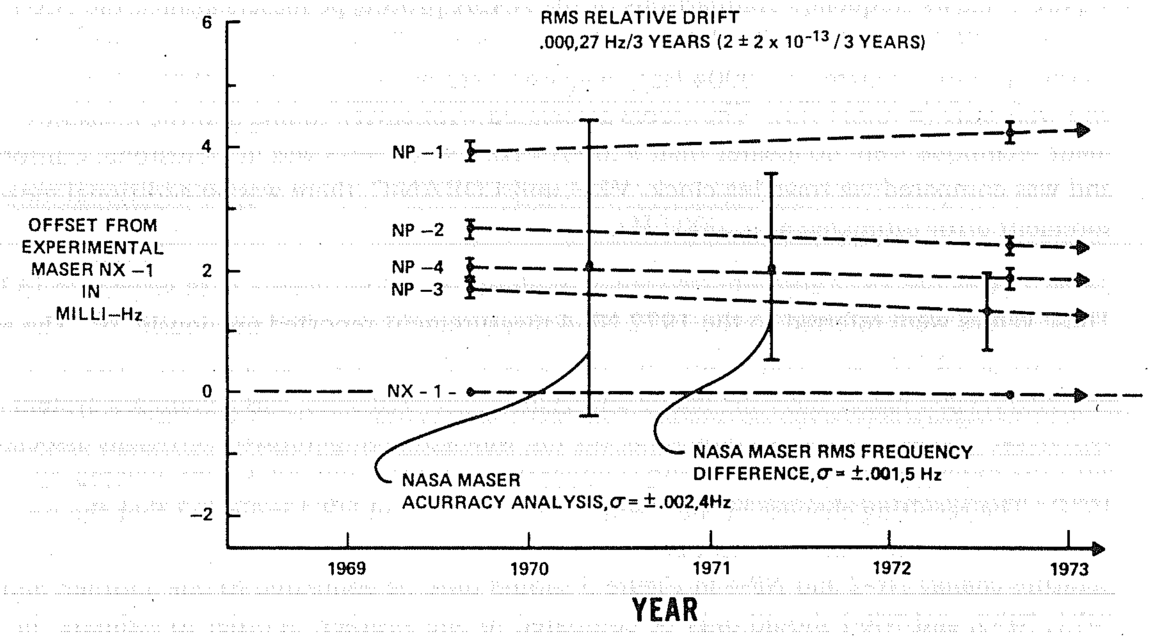

Figure 5. Frequency relationships—NASA NX-1 and NP-1, -2, -3, -4 atomic hydrogen masers.

Table 1

f_H = 1,420,405,751. + table value, H_z

Maser	NP-1	NP-2	NP-3	NP-4	NX-1
Value	.7782	.7764	.7753	.7758	.7740
Average value 0.7760 ± .0024 Hz					

The long-term stability inferred in Figure 5 should be valid if frequency variations due to magnetic field changes are either negligible or estimated by Zeeman frequency measurements. (In the 1972 NP-4/USNO measurement, the magnetic field was checked weekly. The variations in Zeeman frequency indicated an uncertainty in the maser frequency of ± .000014 Hz, with a negligible measurement error.) Under these conditions, a stability estimate for the NASA masers was 2 ± 2 parts in 10^{13} in three years.

An estimate of the intrinsic reproducibility of the NASA maser has been calculated from the RMS variation of all of the maser frequencies from their average frequency. The resulting value was 0.0015 Hz. Reproducibility may be improved significantly if the maser bulbs were removed and recoated; however, this was not done since these masers were in field usage for most of the three years. (For field applications, these absolute differences are easily removed or adjusted to any desired frequency by synthesizers.)

CONCLUSION

Hydrogen masers have already provided significant contributions to PTTI applications due to their excellent short-term stability. Their long-term stability, long operating life, and reproducibility demonstrate their usefulness in generating accurate, stable, and uniform time scales. The use of the hydrogen maser holds promise to improve time and frequency control with greater ease than presently possible with large ensembles of cesium clocks.

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*The value for f_H given herein differs by 0.0003 Hz from the value in Reference (8). This is due to the use of the present value of wall shift temperature coefficient, namely (0.008 ± 0.0003) Hz-in/°C. The previous value, assumed in Reference (8) to be (0.005 ± 0.0003) Hz-in/°C, was that given by Vessot et al. (12), and was only claimed to be valid for the temperatures from 25°C to 40°C, whereas the new value was measured for 35°C to 53°C. The 0.0003 Hz change is far less than the claimed error, so is not of great significance.

Due to operational requirements, immediate before and after measurements were not done, and the 1972 measurements were the first precise frequency comparisons of NP-2 and NP-4 and the other masers subsequent to the temperature changes.

R. Vessot, et al., "An Intercomparison of Hydrogen and Cesium Frequency Standards," IEEE Trans. I&M, Vol. IM-15 No. 4, Dec. 1966.

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