Shuttle Experiment to Demonstrate High-Accuracy Global Time and Frequency Transfer

DAVID W. ALLAN, CARROLL O. ALLEY, JR., RUDOLF DECHER, ROBERT F. C. VESSOT, AND GERNOT WINKLER

Abstract—**The concept of a high-accuracy global time and frequency transfer system is discussed. A hydrogen maser clock onboard a space vehicle combined with a microwave Doppler cancellation system can provide direct frequency transfer with an accuracy of 10^{-14} and time transfer accurate to 1 ns. The addition of short pulse laser techniques provides subnanosecond time transfer accuracy which can be used to calibrate the microwave system.**

INTRODUCTION

THE SUBJECT OF this paper is a space system for high-accuracy global comparison of clocks. The concept and implementation of such a system are being studied by the authors of this paper. The study is presently supported by NASA's Geodynamics Branch of the Office of Space and Terrestrial Applications.

There is a need for a high-accuracy clock comparison system with global coverage. A large number of high-accuracy atomic clocks are now in use around the world. In the western world alone there are approximately 50 hydrogen maser clocks, 2000 cesium beam clocks, and 10000 rubidium vapor cell clocks. The group of users includes national primary standard laboratories in several countries, national and international timing operations, NASA's Deep Space Tracking Net (DSN), metrology laboratories, VLBI for radio astronomy and geodynamics as well as a variety of other users.

The stability and accuracy of precision clocks and primary frequency standards have improved far beyond present capabilities to transfer time and frequency between widely separated clocks, and further improvements in accuracy and stability of clocks can be expected in the future. The present operational mode to compare primary standards in the U.S., Canada, and West Germany utilizes the LORAN C navigation system which cannot provide the high accuracy required and has limited geographical coverage. The most accurate clock comparison method in use now is the transportable clock. This method has many logistic problems and becomes very expensive if high accuracies are required. Various other techniques of high-accuracy clock comparison have been conceived and tested experimentally involving satellites and VLBI. None of these

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D. W. Allan is with the National Bureau of Standards, Boulder, CO.
C. O. Alley, Jr. is with the University of Maryland, College Park, MD.
R. Decher is with NASA, Marshall Space Flight Center, Huntsville, AL 35812.
R. F. C. Vessot is with the Harvard-Smithsonian Center for Astrophysics, Cambridge, MA.
G. Winkler is with the U.S. Naval Observatory, Washington, DC.

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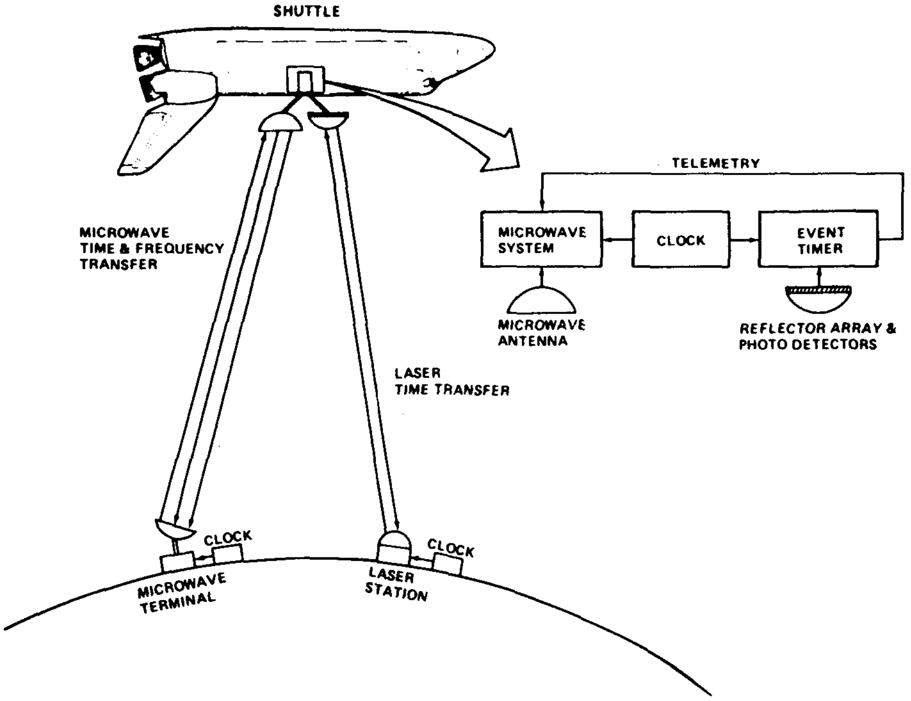

Fig. 1. Shuttle time and frequency transfer experiment (STIFT).

methods can fulfill all of the major requirements for an operational high-accuracy global system. The system to be discussed would meet present and future requirements.

SATELLITE TIME AND FREQUENCY TRANSFER (STIFT) CONCEPT

The proposed satellite time and frequency transfer (STIFT) concept is illustrated in Fig. 1. STIFT can be viewed as an extension of the transportable clock method with a hydrogen maser clock in a space vehicle. Time and frequency transfer between the space clock and a clock on the ground is accomplished by two-way microwave transmission involving three carrier frequencies. The CW microwave system will permit a direct frequency comparison between the space clock and the ground clock with an accuracy of 10^{-14}. This is a unique feature of the STIFT system. A time code modulation will be applied to perform time transfer with an accuracy of 1 ns or better. The user of the system will require a microwave ground terminal located next to the clock to receive signals from and to transmit back to the spacecraft.

In addition, the STIFT system can accomplish time transfer with subnanosecond accuracy using the short-pulse laser technique in conjunction with existing laser ground stations. The laser technique will be used also to calibrate the microwave system. The short-pulse laser method is the most accurate technique of time transfer available. The equipment on board the space vehicle consists of a hydrogen maser clock, a microwave transponder system with antenna, a corner reflector array with photodetectors, and an event timer.

The basic microwave and laser techniques proposed for STIFT have been used with earlier experiments. The microwave technique was developed for the gravitational probe A (GP-A), a joint project of Smithsonian Astrophysical Observatory and Marshall Space Flight Center which was flown in 1976 [1]. The experiment measured the gravitational redshift effect by comparing the frequencies of two hydrogen maser clocks—one clock in a space probe, the other clock on the ground. The demonstrated accuracy of frequency comparison was 10^{-14}. The short pulse laser technique was used in airplane experiments in 1975-1976 by the University of Maryland with support from the U.S. Navy to measure relativistic effects on clocks [2]. The uncertainty in the time comparison of clocks was only a few tenths of a nanosecond. The results obtained from both experiments prove that the proposed performance of STIFT can be achieved without any technology breakthrough.

MICROWAVE SYSTEM

A block diagram of the microwave system is shown in Fig. 2. The key feature of the system is cancellation of the first-order Doppler effect in the frequency comparison loop. The ground clock signal is first transmitted to the spacecraft and transponded back to the ground terminal to obtain the two-way Doppler shift, which is divided by two to generate the one-way Doppler shift, which in turn is subtracted from the one-way space clock downlink signal. The resulting beat signal at the output of the mixer is the frequency difference between the two clocks with the first-order Doppler shift removed. This process also cancels propagation variations in the ionosphere if their duration is longer than the signal round-trip time. The S-band transmission frequencies shown are those used with the gravitational probe A. The three frequencies were selected to compensate for ionospheric dispersion. A single antenna is used at the spacecraft and at the ground station for transmission of the three microwave links.

The frequency transfer uses the phase information of the CW phase-coherent carrier signals. Time transfer is accomplished by modulation of the carrier signals. The time code generated

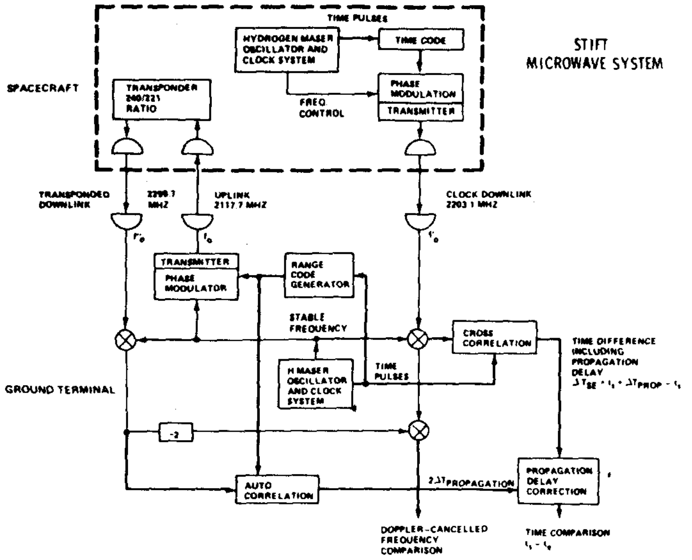

Fig. 2. STIFT microwave systems.

by the space clock is modulated on the clock downlink and compared with the time code of the ground clock. The one-way propagation delay, needed as correction for time transfer, is obtained from the range measurement accomplished by PRN phase modulation of the transponder links. The time difference between the two clocks is derived from the delay of the two time codes.

One important objective is to develop a low-cost, low complexity ground terminal which can be afforded by a large number of users of an operational STIFT system.

LASER SYSTEM

The short-pulse laser technique is the most accurate method of time transfer. Existing laser ground stations can use STIFT for subnanosecond time transfer if they are equipped with an atomic clock and an event timer. Because of the higher accuracy, the short-pulse laser technique can serve as a calibration tool for the microwave time transfer. It should also provide interesting data on microwave versus laser propagation through the atmosphere. Neither the relative velocity nor the distance between space vehicle and ground station enters into the clock comparison.

The laser ground station transmits short laser pulses which are returned by the corner reflector array on the space vehicle. A block diagram of the laser system is shown in Fig. 3. The reflector array is equipped with photodiodes to detect the arrival of the laser pulses. The arrival time t_2' of the pulses is measured in the time frame of the on-board clock by the event timer. This information is telemetered to the laser ground station which measures the time of transmission t_1 and reception t_3 of the laser pulse. The time difference between the space clock and the ground clock is the difference between t_2' and t_2, the mid-point between t_1 and t_3.

SHUTTLE EXPERIMENT

A first step in the implementation of the STIFT system could be an experiment on the Space Shuttle to demonstrate the performance and operation of the system. The experiment package, containing the hydrogen maser clock, microwave transponder with antenna, corner reflector array, and associated electronics, would be mounted on a pallet in the Shuttle bay.

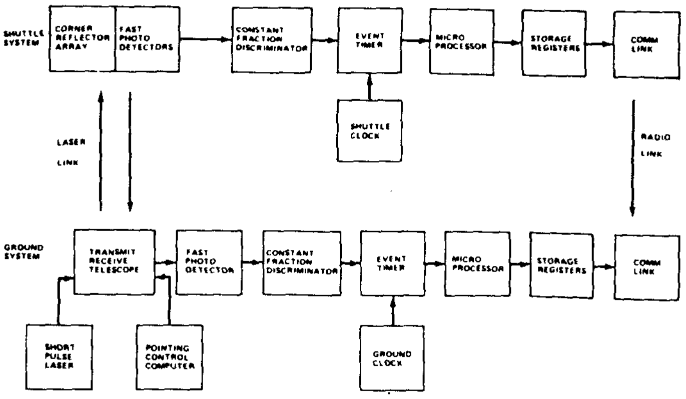

Fig. 3. STIFT laser system.

Shuttle orbits are lower than the desirable optimum for a STIFT experiment but are still adequate to demonstrate the performance and operation of the system. The low orbital altitude results in rather short duration passes over a ground station. A Shuttle mission of maximum orbital altitude (200 nmi = 360 km) and maximum inclination (57°) would be selected for the experiment. The maximum pass duration for this type of orbit is 5.7 min between 10° elevation limits. The 1976 GP-A microwave system achieved a frequency comparison accuracy $\Delta f/f = 10^{-14}$ in 100 s of averaging time (limited by maser stability). Further improvements in hydrogen maser stability have reduced the averaging time for the same accuracy to approximately 20 s. The average pass duration is approximately 4 min for selected locations of ground stations, which is sufficient to perform tests even below the nominal 10^{-14} accuracy level. The pass duration will provide enough time to obtain sufficient data samples for the time transfer portion of the experiment, including the microwave and laser techniques. Participating laser stations need to be equipped with an atomic clock and event timer.

At least two ground terminals should be available for the Shuttle experiment to demonstrate comparison of widely separated clocks. Additional ground terminals would be desirable to permit participation of several potential users of an operational STIFT system. A 57° inclined orbit would provide coverage of the primary standard laboratories, international time service stations, the three DSN stations and various other important laboratories or institutions (Fig. 4). The experiment could be reflown on the Shuttle with a different distribution of ground terminals to permit a wider participation of users.

To achieve the quoted accuracies of frequency and time transfer with the microwave system requires corrections for relativistic effects, including the second-order Doppler and the gravitational redshift. Accurate tracking of the space vehicle will be required to obtain information for calculation of the relativistic effects. For example, to reduce the error contribution of each of the two relativistic effects to 1×10^{-15} the relative velocity between ground station and space vehicle

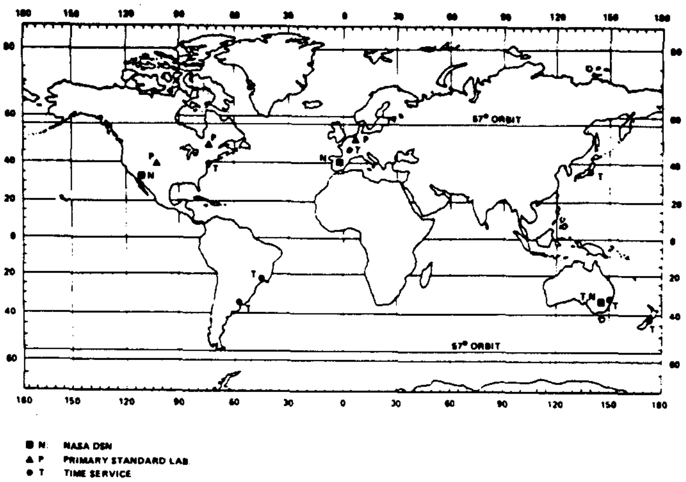

Fig. 4. Station locations.

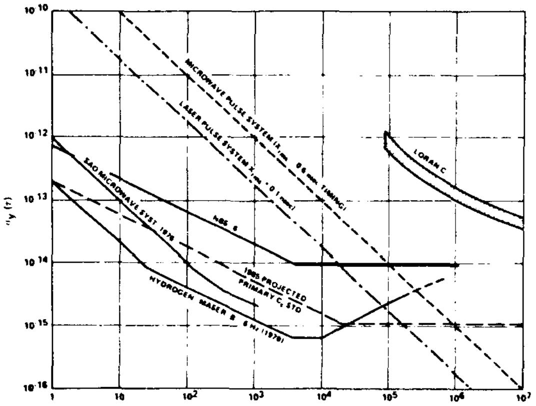

Fig. 5. Frequency stability comparison.

must be known to 1.2 cm/s and the radius of the orbit must be known to 10 m. These accuracies are within the state-of-the-art for a free flying satellite which is the ultimate application of the proposed system. Standard Shuttle orbit data are less accurate, and additional tracking will be needed at least for those orbital segments during which clock comparison data are taken to achieve sufficient accuracy for a demonstration experiment.

STIFT PERFORMANCE

A comparison of the stability of various standards and techniques is shown in Fig. 5. Included are the performances of the 1976 SAO microwave system (GP-A) and the stability of the improved hydrogen maser. The dotted lines represent pulse time transfer systems with accuracies of 0.6 and 0.1 ns, respectively. To compare frequencies with an accuracy of 10^{-14} using a pulse system would require 0.6-ns accuracy of the time transfer if comparisons are made at intervals of 24 h. This shows the advantage of the direct frequency comparison method possible with STIFT.

The desirable characteristics of an operational global-clock comparison system include the following: high accuracy (time transfer 1 ns or better, frequency transfer 10^{-14} or better), low-cost and low complexity ground equipment, low-operational cost, global coverage, frequent or continuous access, weather independence, and single terminal operation. The STIFT concept can meet all of these requirements better than other proposed or existing systems and, in addition, provides direct frequency transfer with high accuracy.

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David W. Allan was born in Mapleton, UT, on September 25, 1936. He received the B.S. degree in physics from Brigham Young University, Provo, UT, in 1960, and the M.S. degree in physics from the University of Colorado in 1965.

In 1960 he joined the Atomic Frequency and Time Standards Section of the National Bureau of Standards, Boulder, CO, where he worked with ammonia beam masers and related quantum electronic devices. Since 1962 his work has been directed toward the development of the atomic time scale systems for the National Bureau of Standards, derived from the National Bureau of Standards Frequency Standard and used to control radio stations WWVL, WWVB, WWV, and WWVH. He is currently the Chief of the Time and Frequency Coordination Group of the Time and Frequency Division in the National Bureau of Standards.

Mr. Allan is a member of the Scientific Research Society of America, Sigma Xi, and the International Radio Consultative Committee (CCIR). He received the Department of Commerce Silver Medal award, October 29, 1968, "for contributions to the NBS atomic time scales and the understanding of the statistics of atomic frequency standards." In 1969 he received a visiting professor's grant from the Italian government to lecture and work at Istituto Elettrotecnico Nazionale Galileo Ferraris in Torino, Italy. In 1976 he was awarded the *Industrial Research* IR-100 award for developing a picasecond time difference instrument. In 1977 he was an invited speaker at an International Symposium on $1/f$ noise held in Tokyo, Japan. In 1978 he received an Air Force invention award, and was invited, along with a colleague, to give a paper at the International Union of Radio Science (URSI) in Helsinki on the "Practical Implications of Relativity for a Global Coordinate Time Scale."

Carroll O. Alley, Jr. was born in Richmond, VA. His undergraduate education was at the University of Richmond in mathematics and physics where he was elected to Phi Beta Kappa. He went to the graduate school of Princeton University on an Eastman Kodak Fellowship in electrical engineering, where he also studied theoretical and experimental physics, receiving the Ph.D. degree in physics for research on optical pumping and microwave and radio frequency resonances in rubidium vapor. This work contributed to the development of the rubidium gas cell atomic clock.

He taught Electrical Engineering at Princeton University, Princeton, NJ, Optics and Physics at the University of Rochester, Rochester, NY, where he initiated a research program in lasers from 1960 to 1963, and is now Professor of Physics in the Physics and Astronomy Department of the University of Maryland at College Park, MD where he has taught and conducted research since 1963 as director of the research group in atomic physics and quantum electronics. His research interests include the use of lasers, atomic clocks, and single photoelectron detection techniques to conduct fundamental experiments in physics, astronomy, and geophysics. In recent years, he has pioneered in teaching some of the fundamental concepts of General Relativity in introductory physics courses, basing the approach in part on his measurements with atomic clocks. He has also developed a new course for physics and astronomy seniors and graduate students on curved spacetime, experimental gravitation, and relativistic astrophysics. He has served as advisor to the Department of Defense, the Air Force Systems Command, the National Bureau of Standards, the National Academy of Sciences, and NASA. He has been active in the International Astronomical Union, the International Union of Geodesy and Geophysics, and the Committee on Space Research (COSPAR) of the International Council of Scientific Unions.

In 1973 the National Aeronautics and Space Administration awarded Dr. Alley its Medal for Exceptional Scientific Achievement for his role as Principal Investigator in the development of the Apollo II Laser Ranging Retro-Reflector Experiment by his group at the University of Maryland, the Goddard Space Flight Center, the MacDonald Observatory of the University of Texas, the National Bureau of Standards, and other institutions. He received an honorary Doctor of Sciences degree from the University of Richmond, Richmond, VA, in 1978.

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Rudolf Decher is a native of Germany and received the M.S. and Ph.D. degrees in physics from the University of Wuerzburg, West Germany, in 1950 and 1954, respectively.

From 1955 to 1960 he was involved in the development of electronic measuring techniques and equipment in industry in West Germany. Since joining NASA's Marshall Space Flight Center in Huntsville, AL, in 1960, he has held several positions in research and development. From 1960 to 1969 he was involved in the development of RF systems, radio tracking, and navigation and guidance systems for the Apollo Program, including system engineering and development of the Instrument Unit of Saturn launch vehicles. Since 1970 he has been Chief of the Space Physics Division in Space Sciences Laboratory. His Division is responsible for the development of scientific flight experiments in various discipline areas of space science. In recent years his research activities have included the development of gravitational physics experiments. He was the project scientist for the Gravitational Prove A (Gravitational Redshift Experiment) which was launched in 1976.

Dr. Decher is a member of the American Institute of Physics and the American Institute of Aeronautics and Astronautics.

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Robert F. C. Vessot was born in Montreal, Que., Canada, on April 16, 1930. He received the B.A., M.Sc., and Ph.D. degrees in physics from McGill University, Montreal in 1951, 1954, and 1959, respectively.

From 1956 to 1960 he was a staff member of the Department of Space and Research at Massachusetts Institute of Technology, Cambridge, where he worked on cesium frequency standards. In 1960 at Varian Associates, Beverly, MA, he initiated a program of research and development involving the then newly-invented hydrogen maser, continuing that work at the same location for Hewlett-Packard. In 1969, he moved the Hydrogen Maser program to the Harvard-Smithsonian Center for Astrophysics in Cambridge, MA, and was Principle Investigator of the successful 1976 Gravitational Redshift Spaceprobe experiment. He continues to work in the development of improved frequency standards and their application to astrophysical measurements.

Dr. Vessot is a member of American Physical Society.

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Gernot Winkler is a native of Austria, and received the Ph.D. in astronomy and physics from the University of Graz, Austria, in 1952.

After employment at the University observatory as an assistant to the director, he worked in industry. In 1956 he came to the United States and was a consultant for atomic frequency control at the Signal Corps Laboratories. He held two executive positions in communications and remote sensing research, followed with his appointment as director of Time Service at the U.S. Naval Observatory in 1966. He participated in Arctic Communications Research in Greenland and Anarctica. He worked also on VLF propagation where he (jointly with F. Reder) pioneered the use of atomic cesium clocks for phase velocity measurements and as portable clocks over global distances. He has 6 U.S. patents and over 50 publications to his credit.

Dr. Winkler has been President of Commission 31 (TIME) of the IAU and is a member of Commissions 4 and 19 (Rotation of the Earth). He is an active participant in the work of URSI, IUGG and CCIR (Study Group VII). He has been the USNO representative in the CCDS since 1967 and has been a member of various National Research Council advisory committees. He was elected a fellow of the IEEE in 1970.