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WORLDWIDE TIME AND FREQUENCY SYNCHRONIZATION BY PLANNED VLBI NETWORKS

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The general concept of Very Long Baseline Interferometry (VLBI) is shown in Figure 1. Two widely separated radio antennas receive radiation emitted from the same distant quasar. The receivers at each station use a hydrogen maser frequency standard clock for generating local oscillator signals for translating the received quasar energy down to baseband for recording. The frequency standard is necessary to assure that the two receiving systems are operating on very close to the same frequency. The output of each receiver is digitized and recorded on a magnetic tape. The magnetic tapes are then brought together and processed in a correlator. Since the received quasar signals are wideband noise, a sharp correlation peak occurs when the two signals are in time phase. In the example illustrated in Figure 1, the signal received in the left hand antenna is delayed by an amount τ from the signal received in the right hand antenna. Thus, by inserting a delay of τ in one arm of the correlation processor, the two signals will be brought into coincidence and a peak correlation occurs. The amount of delay necessary to produce correlation is dependent upon the position of the quasar relative to the two antennas and upon the length of the baseline between the two antennas. In actual observations, the two antennas are mounted on the earth which is rotating. Thus, the frequencies are doppler shifted and the delay required for correlation is continuously changing with time. Thus, in the processor, one determines both the differential delay and the delay rate of the signals propagating from the source to each site. Measurements of several different quasar sources with the same baseline can provide a sufficient number of independent observations to enable one to solve for the clock offset and clock drift rate in addition to the baseline vector and other parameters such as UT.1 and polar motion. With hydrogen maser frequency standards, the offset and drift terms are sufficient to describe the frequency during the 24-hour observing period.

At the 1974 PTTI meeting, T. Clark presented the very accurate baseline determinations and clock synchronization results obtained from the Quasar Patrol observations at X-band with the Goldstone-Haystack baseline, shown in Figure 2. The primary objective of the Quasar Patrol is to measure quasar structure. Thus, three or four stations usually are operated simultaneously as a VLBI array, as indicated by the dotted lines in Figure 2. In addition to Goldstone and Haystack, stations at Fairbanks, Alaska; Greenbank, West Virginia; and Onsala, Sweden were used. This full array of stations is being shown because it is a fairly widespread network that spans a large part of the globe.

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All of these VLBI stations had hydrogen maser frequency standards. The solutions for the relative clock epochs between stations in the Quasar Patrol had an RMS residual of about 0.3 nanosecond. However, we estimate that the accuracy of the clock epoch determination was about one nanosecond, due to several small systematic factors. An example of the systematic factor is the environmentally dependent change in the electrical length of the cable carrying the standard frequency signal from the hydrogen maser to the receiver input at the feed of the antenna. Recent measurements at NRAO indicated a change of about 4 cm in electrical length of the standard frequency cable during a VLBI observing session of 24 hours.

The accuracy demonstrated for baseline length determinations was of the order of 16 cm. Studies conducted by the Goddard/Haystack/MIT group indicate that improved calibration and monitoring techniques will reduce the systematic factors by an order of magnitude; use of a much wider band recorder will improve the signal-to-noise ratio, and simultaneous monitoring of tropospheric and ionospheric propagation characteristics will reduce propagation uncertainties by an order of magnitude. This indicates that it should be feasible to make baseline length determinations with VLBI to an accuracy of a few centimeters.

Because of this potential, NASA has started a VLBI Project, called the Pacific Plate Motion Experiment (PPME). The primary objective of PPME is to measure directly the movement of the central part of the Pacific Plate relative to the North American Plate as indicated by the motion of the island of Kauai, Hawaii. The very long term movement of the Pacific Plate is estimated from current tectonic plate motion models to be about 8 cm/year toward the northwest from the East Pacific Rise (large arrow in Figure 3). However, there has been no direct measurement of this movement except for local geodetic surveys along bounding faults, such as the San Andreas; in addition, it is not known how this motion varies over relatively short (3 year) periods of time. Such variation is important not only scientifically but because short-term variations in plate motion of the center of the plate with respect to its edge are an indication of strain buildup along bounding shear faults that lead to earthquakes.

The PPME will use VLBI systems to measure very accurately (5 cm) the baselines between a station in Kauai, Hawaii, on the Pacific Plate, and stations on the North American Plate at Fairbanks, Alaska; Goldstone, California; and Haystack Observatory, Massachusetts, as shown (by solid lines) in Figure 3. Possible minor local movements of Kauai will be allowed for by geodetic surveys in the Hawaiian Islands. Because the western boundary of the North American Plate is a broad one, intraplate movements of the Alaskan and Californian stations will be measured by VLBI measurements of baselines to the Haystack Observatory (and possibly a station at Ft. Davis, Texas as shown by the dotted lines in Figure 3), well within the North American Plate.

Another objective is to determine by direct VLBI measurement the motion of a station at Kashima, Japan relative to the three stations on the North American Plate and relative to Kauai, Hawaii. Japan is in the boundary zone between the Pacific and Eurasian Plates where the Pacific Plate is believed to be consumed by subduction under the Japanese Islands, giving rise to frequent and often catastrophic earthquakes.

In order to achieve the 5-cm baseline determination accuracy, the instrumental and propagation errors will be reduced by augmenting the present type of VLBI systems with the following new capability: improved instrument calibration, microwave water vapor radiometers for tropospheric path length determination, and simultaneous dual frequency (8400 and 2300 MHz) reception for ionospheric path length determination.

All of the early VLBI experiments utilize large, high gain antennas which give sufficient signal-to-noise ratios for high accuracy VLBI. The PPME objectives require comparable signal-to-noise ratios when using the 9-m antenna in Kauai and the 26-m antenna in Fairbanks. This will be achieved by using a much wider bandwidth data system, called the Mark III system. In addition to the wideband data capability, the Mark III system will contain the VLBI sequence program and control for automated operation of the total VLBI system.

Hydrogen maser frequency standards will be used at all of the stations. A new calibration system will be used to accurately monitor the internal system delays at the picosecond level.

You can recognize that this particular network will automatically, as a fallout, establish time synchronization for all of these stations to the fractional nanosecond level.

We plan to be operational with this system in late '77 or early '78, and to conduct observations roughly every three months in order to track the motions of the Island of Kauai.

Another NASA program that is being implemented by the Jet Propulsion Laboratory is shown in Figure 4. This shows the baselines from the 210-foot antenna at the Goldstone Station in California to the DSN 210-foot antennas in Madrid and Australia. JPL is implementing VLBI in those stations to form a network of three stations for the precise determination of polar motion and UT.1. They also will use the dual S/X frequencies. As a matter of fact, the Goldstone station that will be used for the PPME is the DSN network station. It is the first station equipped with the dual S/X frequency capability. DSN will use water vapor radiometers, wide bandwidth synthesis, hydrogen masers and electronics calibrations very similar to the PPME. In fact, we are working to make these stations compatible with the PPME stations and vice versa.

This DSN VLBI capability is expected to be operational in 1977 for determining polar motion for deep space navigation. The operation that is envisioned is that on a normal basis the measurements of polar motion and UT will be made once a week. During critical mission phases, like planetary encounter, the measurements will be made on a daily basis.

In addition, of course, this VLBI will be used to synchronize the DSN clocks. The capability will be there for subnanosecond type synchronization.

Figure 5 is a world map showing the VLBI networks for PPME (solid lines), DSN (dashed lines) and Quasar Patrol (dotted lines). Common stations, such as Goldstone, form the tie between the networks. The Haystack Observatory station is involved in astronomical VLBI with many other radio astronomy stations such as Greenbank, W. Virginia; Owens Valley, California; Fort Davis, Texas; San Paulo, Brazil; Crimea, U.S.S.R.; and Algonquin Park, Canada. The Max-Planck-Institut fur Radioastronomie, Bonn, Germany, has indicated their desire to use their 100-m antenna for a VLBI link with Haystack. The NASA stations at Santiagc, Chile and S. Africa are potential VLBI terminals in the future. All of these site locations are marked on Figure 5 with small circles.

All of the stations joined by lines in Figure 5 will have hydrogen masers and comparable VLBI capability in the late '70's. In addition, many of the radioastronomy observatories that are active in VLBI have expressed an interest in obtaining hydrogen masers and the more advanced VLBI systems that NASA is planning to implement.

Looking at this, you see a rather extensive worldwide network of stations, probably all of them with hydrogen masers. This network in the VLBI mode will be synchronized to the subnanosecond level and will be periodically resynchronized, some on a weekly basis and some on a monthly basis. This forms a rather elaborate, far-reaching network with precise time and frequency synchronization.

So I would like to ask this audience what the time and frequency field would recommend for utilization of such a network for precise time and frequency applications. NASA strongly feels that there will be a significant capability here and there is probably an interest outside of NASA to make use of such a capability. I would like to hear from any of you who wishes to join in with us and work with the time and frequency aspects of the problem.

With a VLBI network, there are several things that would have to be done to make it an operational time and frequency network. For example, there is no time/frequency input or output to the present VLBI networks. The VLBI data is recorded, shipped to a central processing facility, and analyzed at a later date for clock offset and other parameters. It is usually several months after the data is taken that the analysis is completed. This delay reduces the usefulness of the output for many time and frequency applications. I envision that there would have to be direct input/output ties with the user organizations and with other ensembles of frequency standards in order to utilize the VLBI networks for precise time and frequency applications.

I would like to receive comments from any of you that are interested in working in a cooperative manner in this area.

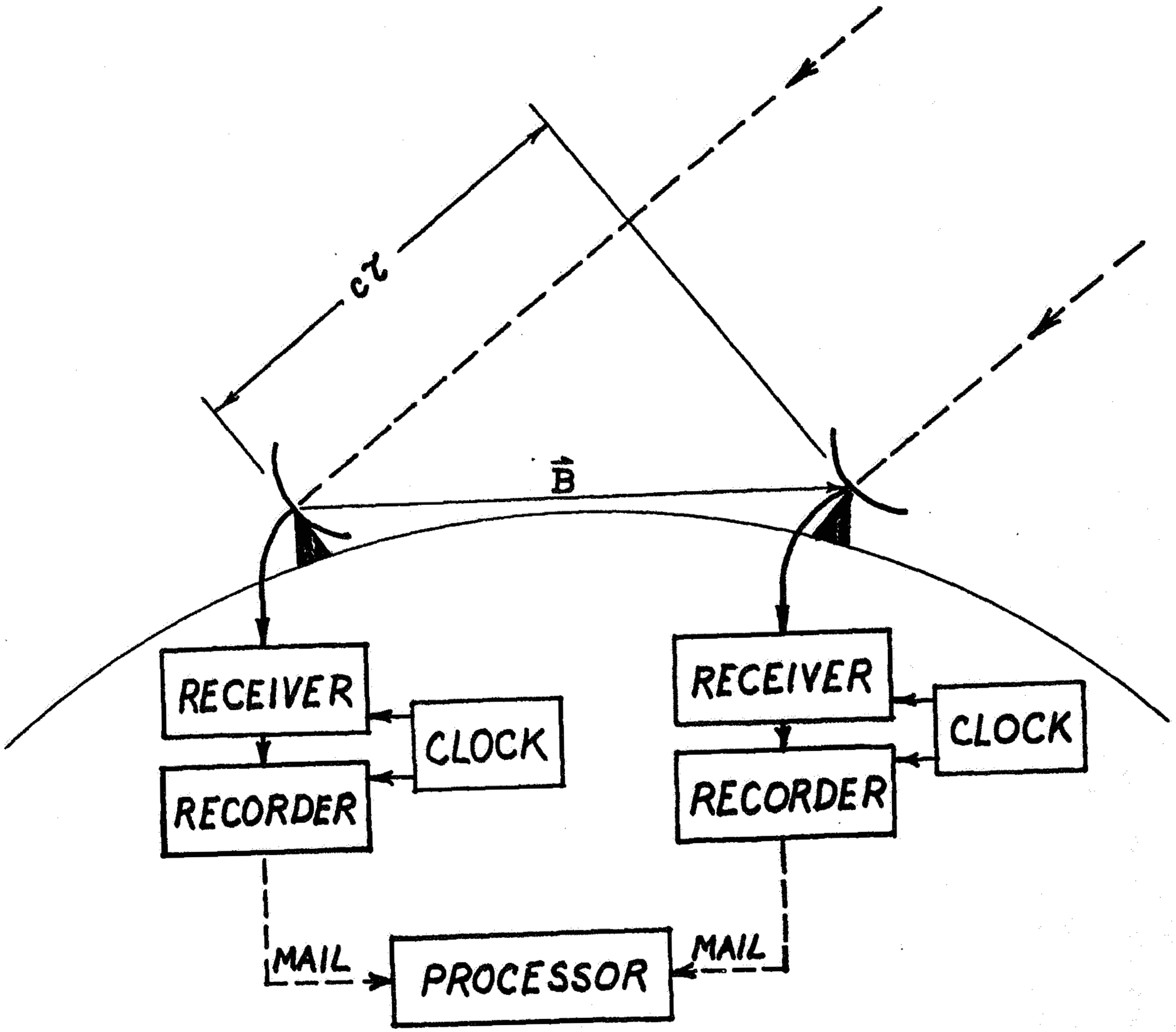

Figure 1. Very-Long-Baseline Interferometer Diagram

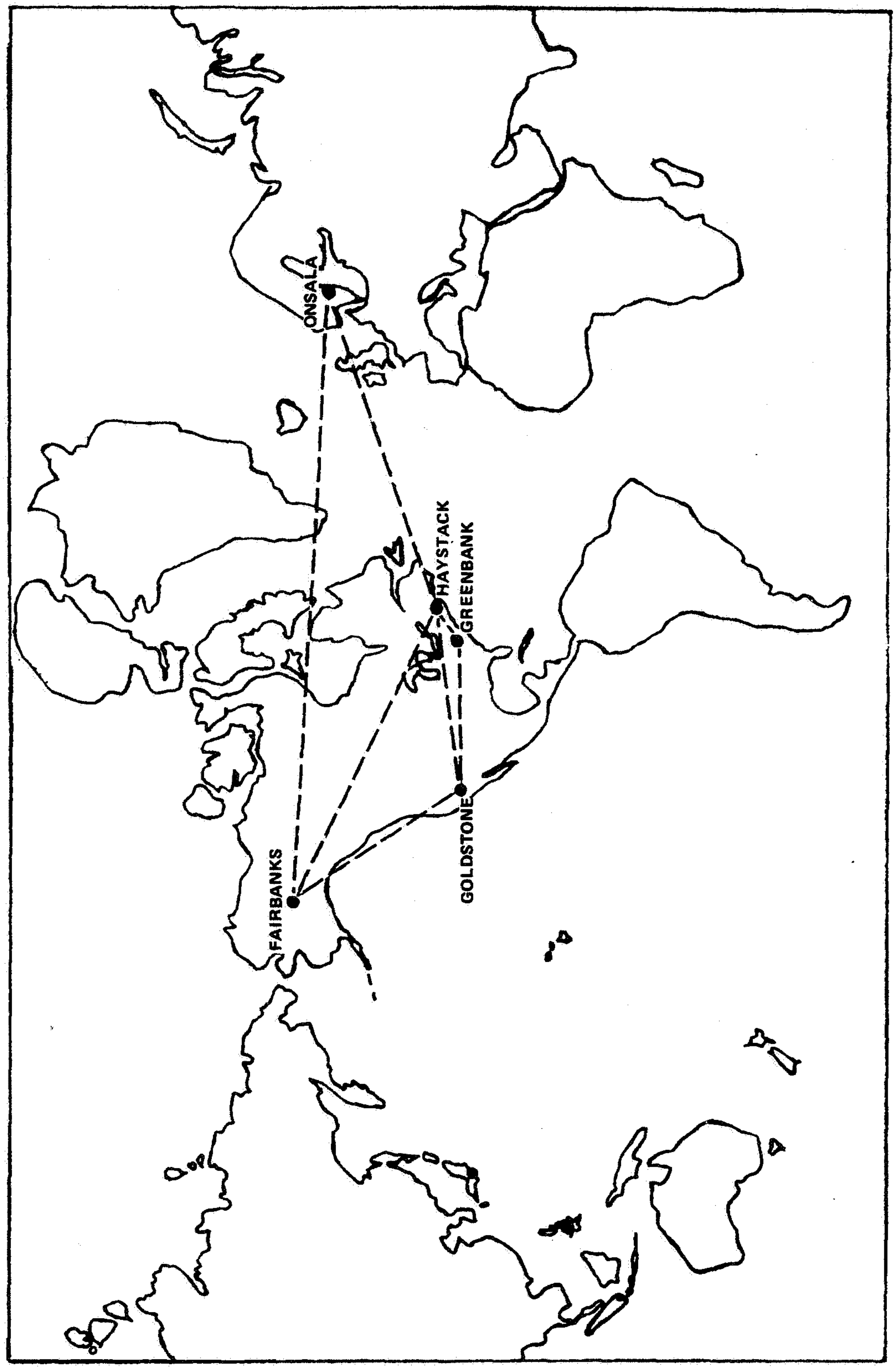

Figure 2. Stations for Quasar Patrol

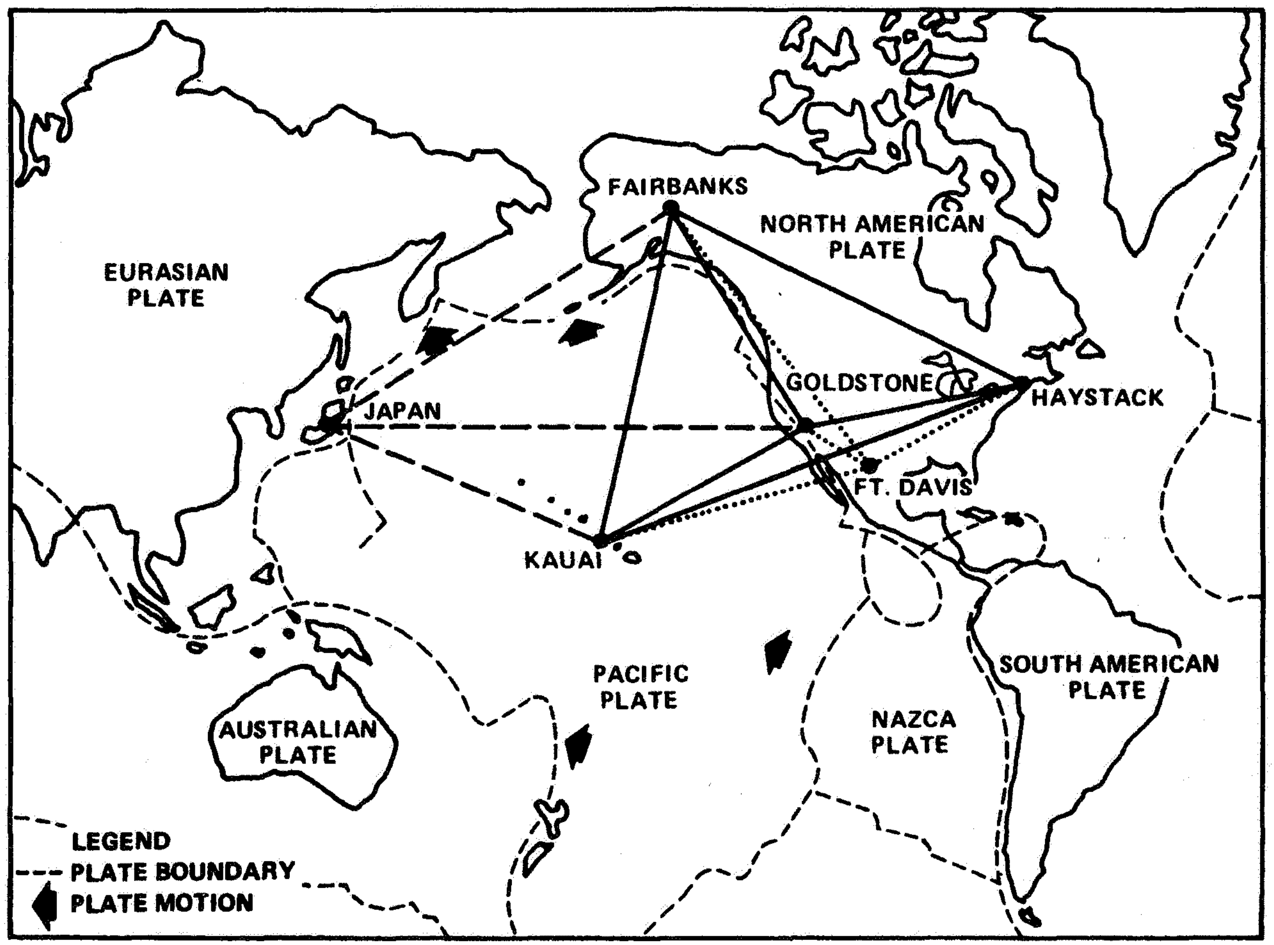

Figure 3. Antenna Configuration for Pacific Plate-Motion Experiment

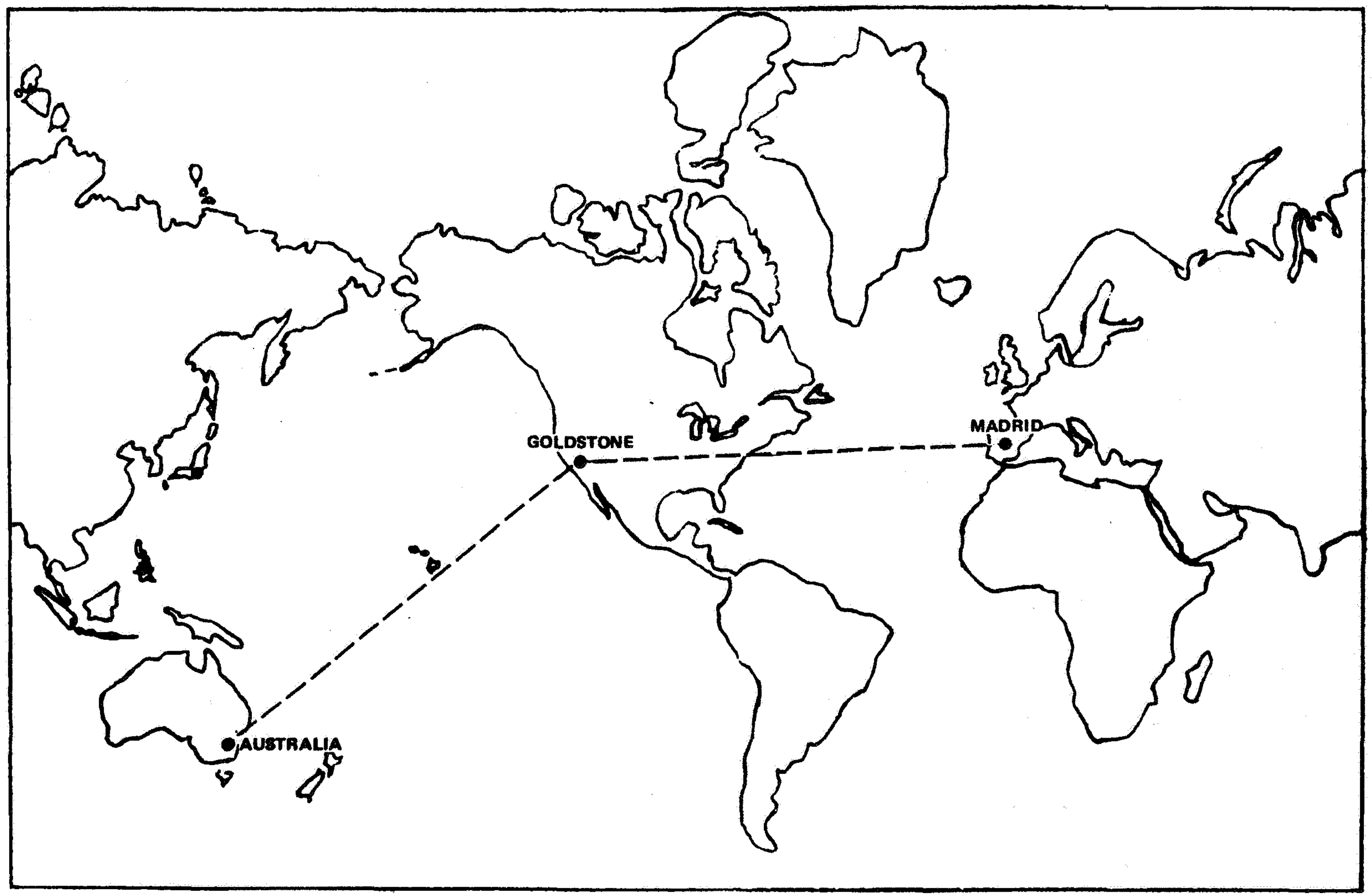

Figure 4. DSN VLBI Network

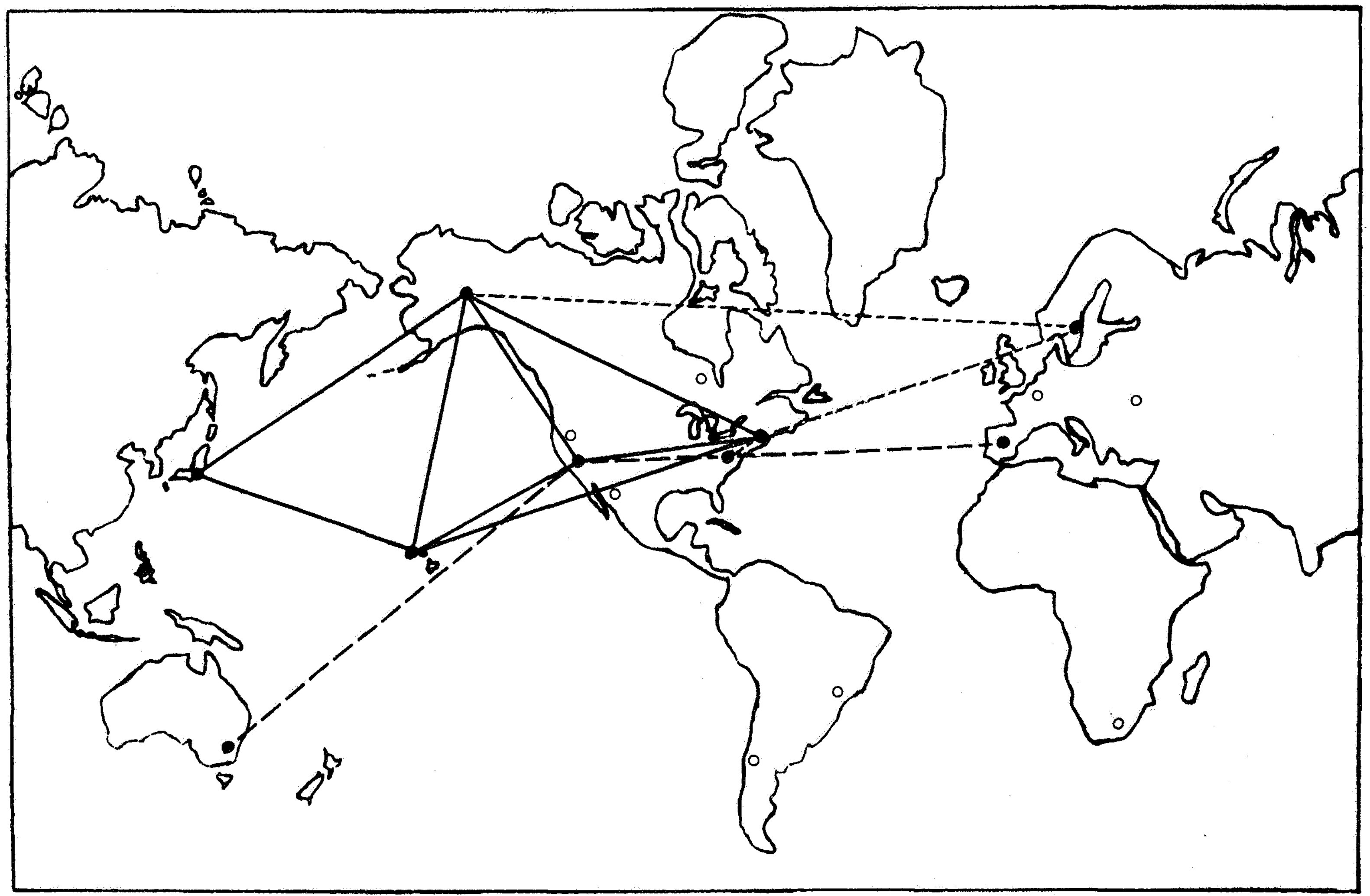

Figure 5. World Wide VLBI Networks