Preliminary Demonstration of Precision DSN Clock Synchronization by Radio Interferometry

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Radio interferometry can be used to measure the offsets between the clocks at the various stations of the DSN, and to monitor the rates of the station frequency standards. A wideband digital data acquisition system has been developed to measure the clock offsets to the 10-ns accuracy required to facilitate three-way spacecraft ranging, to monitor the hydrogen maser frequency standard rates to 1 part in 10^{14}, and to potentially reduce operational costs by replacing the current DSN Operational Time Sync System. Three experiments have been conducted with this system, two short-baseline experiments at Goldstone and one long-baseline experiment between Goldstone and Australia. All achieved subnanosecond resolutions. These accuracies were independently confirmed to within about 3 μs, as limited by the accuracy of available independent measurements.

I. Introduction

Radio interferometry can be used to monitor the offsets between the clocks and the frequency standards of the DSN stations, as first demonstrated in the DSN by Goldstein (Ref. 1). A wideband digital data acquisition system (WBDAS) which has been developed for this purpose is described here, and the results of three experiments are presented. All three experiments achieved subnanosecond resolutions, with accuracies confirmed to within 3 μs by independent measurements. The goal of the development effort is to demonstrate the ability to routinely measure the clock offsets to the 10-ns accuracy required for three-way spacecraft ranging, and to monitor the hydrogen maser frequency standard rates to 1 part in 10^{13} with a few minutes of observing time and to 1 part in 10^{14} over approximately 1 week.

The fundamental process of radio interferometry is the observation of radio emissions from a quasar or other radio energy source simultaneously at two (or more) antenna stations. The difference in the time of arrival of the signal at the stations and the rate of change of the time difference are measured by cross-correlating the noise-corrupted signals at the receiver outputs. The time difference and its rate of change are also calculated from the source observing geometry, and the differences in the measured and calculated values are attributed to the station clock and clock-rate offsets, plus errors in geometry, etc. Multiple observations of several radio sources can be used to solve for the source positions, the station locations, and Earth's orientation (UT1 and polar motion) (Refs. 2, 3). When these parameters are adequately known a priori, the clock synchronization accuracy which can be achieved in a single measurement is limited primarily by uncertainties in the propagation delays through the transmission media, and is thus comparable to the transmission medium calibration accuracies achieved for spacecraft tracking (see, e.g., Ref. 4).

The data acquisition system also can limit the achievable accuracies. Wide bandwidths are required for accurate time delay estimates, and long time durations are required for accurate frequency offset or "fringe rate" measurements, which are used to estimate the rate of change of time delay. It is desirable to utilize the full available bandwidth of the receiving systems – tens of Megahertz – and to have a time duration of tens to hundreds of seconds per observation. Since the data must be recorded at both stations and then brought together for processing, continuous recording of the full bandwidth would require extremely high recording rates and densities. Fortunately, however, it is not necessary to record the full time-bandwidth space, and various schemes exist for selecting portions of the time-frequency space to be sampled and recorded.

One method for sampling the time-frequency space is called bandwidth synthesis (Refs. 5-8). Two or more narrow bands of the spectrum are sampled and recorded, either sequentially or in parallel, and time delay estimates are constructed from the fringe phase measurements at the various frequency bands. This utilizes the fact that group delay is the derivative of phase delay with respect to frequency. Efficient utilization of the recording medium is achieved. For clock synchronization, however, the method appears to require elaborate phase calibrations of the entire receiving system.

The wideband digital data acquisition system spans the time-frequency domain using the technique of full band sampling with burst recording. The full instantaneous bandwidth of the receivers is sampled, up to a bandwidth of 55 MHz, but not all the data samples are recorded. Short bursts of data samples are stored in a high-speed buffer. Then, when the buffer is full, sampling is inhibited and the buffer is emptied through a small computer onto digital magnetic tape. The full bandwidth and time duration are utilized, but the average data rate is matched to the recording rate by deleting segments of the time domain. Per bit of data, the same time delay resolution is achieved as if the full bandwidth were sampled continuously. This method has been known for some time (Ref. 5), and has been demonstrated in the DSN with fairly narrow bandwidths, with supporting analysis (Refs. 9-11). The WBDAS implementation has become practical with the improved technology in high-speed analog-to-digital (A-D) conversion, digital filtering, and data storage.

A major advantage to full-bandwidth sampling over bandwidth synthesis is that receiving system phase calibrations are not required, although the actual clock offsets can be separated from the station group delays only if the group delays are calibrated, similarly to the ranging system zero delay system (Ref. 12). Clock rate offsets can be measured without delay calibration, provided only that the delays are stable. Furthermore, three-way ranging, the major navigational method requiring high-resolution clock synchronization, does not require station delays to be separated from the clock offsets, provided that sampling of the ranging and very-long-baseline interferometry (VLBI) data is accomplished at the same point in the system.

Of course, the time-bandwidth space required for an experiment can also be spanned by methods combining bandwidth synthesis and burst storage. This could result in bandwidth synthesis processing, but with frequency bands wider than could be accommodated continuously on the recording medium. The WBDAS is well suited to such applications.

II. WBDAS System Description

A block diagram of the wideband digital data acquisition system is shown in Fig. 1. The signal input to the system, from the radio source, is at IF, either from a Block III receiver 50-MHz IF amplifier, a Block IV receiver 55-MHz IF amplifier, or another receiver with a comparable IF frequency. The signal is digitally demodulated, filtered, sampled and buffered in a digital memory, and then written onto digital magnetic tape through a station computer. The data are later transmitted to JPL over the GCF or by airmail. Using the GCF, clock synchronization could be achieved in near-real time, since less than 10^6 bits are usually required (Refs. 9, 10, 11, 13).

The input signal from the receiver IF amplifier is sampled at the 50- or 55-Ms/s rate by each of two three-bit A-D converters. The A-D conversion times are controlled directly from 50- or 55-MHz reference signals, derived from the station frequency standards, or by dividing the 100-MHz output of a hydrogen maser by 2. The two converters effectively sample 90 deg out of phase, at the sampling frequency. This demodulates the signal to baseband, extracting the quadrature phase components of the "narrowband" process, in a manner similar to the Mu-II ranging system (Ref. 14). The 90-deg phase shift is actually accomplished by delaying the signal to one converter in a cable of the correct length, which is more stable than delaying a clock signal digitally. The total sampling rate of 100 or 110 Ms/s is sufficient for receiving bandwidths of up to 55 MHz.

The overall phase stability of the input signal paths, the sampling clocks, and the A-D converters have been tested as better than 0.3 deg/°C at 50 MHz, or 20 ps/°C.

Whenever desired, the sampling rate at the input to the digital buffers can be reduced to below the A-D converter sampling rate by digital low-pass filtering of the raw samples with the filter bandwidth controlled by the computer. Specifically, these filters sum N consecutive samples, $1 \leqslant N \leqslant 2^{16}$, similar to the operation of an analog integrate-and-dump filter. The bandwidth is reduced to $f_o/(2N)$ and the final sampling rate to f_o/N in each channel, where f_o is the A-D converter sampling rate. Only the sign bits of the filter outputs are used in the final samples, which are stored in the 4096-bit buffer. This is typical of radio interferometers because there is more information per bit in the sign of the number than in the less significant bits.

The data samples are precisely time tagged by a high-resolution clock contained within the data acquisition system. The clock is derived from the same 50- or 55-MHz reference input used by the A-D converters, and is included because no clock of adequate resolution and stability is available from the Frequency and Timing Subsystem (FTS). The clock is initially synchronized to the 1-p/s signal from the FTS, and then allowed to free-run from the IF reference. When the FTS 1 p/s and the IF reference are derived from the same frequency standard, the 1-p/s output of the high-resolution clock should remain in phase with the FTS 1 p/s to within the resolution of the FTS pulse. This provides a monitoring capability for both systems. Sometimes the WBDAS frequency reference may not be derived from the station standard, for example, when a hydrogen maser is available but is not operational as the prime station standard. In this case, the WBDAS 1-p/s output and the FTS 1 p/s can be used to monitor the phase and frequency offsets of the two standards.

Not only must the data samples be precisely time tagged, but the exact times at which data sampling is initiated at the two stations must be carefully coordinated, since the buffer can be filled in about 40 μs at the highest sampling rates. To assure that the same data are sampled at the two stations, the relative time of arrival of the signal at the stations must be predicted to within a few microseconds and sampling initiated at times offset by this amount. This is accomplished by having each computer predict the geometric time delay from the station to the geocenter, using the station location and the source position of date, and offsetting the sampling time by this amount from the nominal times. The station clock offsets must also be accounted for, and the widest bandwidth should not be used when the uncertainty in the a priori knowledge of clock offset exceeds the normal uncertainty of 2-10 μs. Precise timing is accomplished by reading the station binary-coded decimal (BCD) clock in the computer and the microsecond clock in the hardware, with sampling initiated at the first tick of the A-D converter clock after the microsecond clock reaches the computer selected count.

Besides the data samples, the hardware transmits some performance monitoring data to the computer, including the microsecond at which the buffer was completely full. This provides a check on the timing and filter bandwidth, and is written onto the digital tape along with other header information.

The experiments to date have utilized the station Telemetry and Command Processor Assembly (TCP) computers, although the hardware and software are also compatible with the Digital Instrumentation Subsystem (DIS) computers. Since some of these computers have tape units which operate at only 79 b/cm (200 b/i), the data recording rate has been limited to about 56 kb/s. The hardware is also completely compatible with the standard DSN minicomputer, since all communication is over the DSN standard interface. It will thus be practical to upgrade the data rate to about 640 kb/s when minicomputers with 630-b/cm (1600-b/i) tape units become operational.

III. Experiment Results

Three experiments have been conducted with the wideband system, two short-baseline experiments at Goldstone and one long-baseline experiment between Goldstone and Australia. The objectives of these experiments were to develop and demonstrate the capability of the combined data acquisition hardware and software, and the processing software. All experiments were successful, and achieved subnanosecond time delay resolutions. This resolution is not to be confused with accuracy, because the station and propagation medium delays were not calibrated, and the source position uncertainties were significant on the long baseline. In all cases, the estimated clock offsets agreed with the standard DSN measurements to within 3 μs, which is within the accuracies of these measurements and the expected variations in station delays.

All of the experiments were at S-band, using rubidium frequency standards.

A. First Experiment

The first experiment was performed on the short baseline between DSS 11 and DSS 14 at Goldstone on December 14, 1975, in conjunction with an Astronomical Radio Interferometric Earth Surveying (ARIES) experiment. The primary purpose of this experiment was to obtain sufficient data to develop and test the processing program, and to demonstrate that the hardware/software system was operating properly. The RF signal bandwidths were restricted to about 8 MHz by using the telemetry C-channel outputs of the Block III receivers at both stations. The local oscillator references were derived from the rubidium frequency standards by replacing the voltage-controlled oscillator (VCO) output signal with 23.33333333 MHz from Hewlett Packard 5100 frequency synthesizers. No attempts were made to do any station calibrations, except to obtain a priori clock offsets with respect to the DSN master clock, as is routinely done by microwave links.

Successful results were obtained for a total of eight observations, using six different radio sources and digital filter bandwidths of 0.495, 3.34, 5.56, and 10.0 MHz. The estimated offsets between the station clocks are shown for these eight runs in Fig. 2, for the 3 min of data using a digital filter bandwidth of 5.56 MHz. The ordinate scale, $T_{14} - T_{11}$, is the estimated clock reading at DSS 14 minus the reading at DSS 11 made at the same time. The measured clock offsets of about 8.6 μs for $T_{14} - T_{11}$ agree to within 1.6 μs of the a priori value of 7 μs determined from the microwave link measurements, relative to the DSN master clock ($T_{14} - T_{DSN} = -1$ μs and $T_{11} - T_{DSN} = -8$ μs). The error bars indicate the 1-σ sample deviations, as determined by dividing the 180 s of data into several shorter intervals. The slope of the line fitted to the data was determined from the fringe rate data. This indicates the consistency between the two data types: frequency and time delay.

One result of the first processing of the data from this experiment was to emphasize the need to model the receiving system passbands to get an estimate of the signal cross-correlation function. Although optimum processing requires knowledge of the cross-correlation function, the data were first processed with only the digital filter effects modeled. Failure to model the receiver passbands when the filter bandwidths were comparable to the receiver bandwidths resulted in a detector function which was sometimes bimodal, causing extraneous results and a higher than expected sample deviation. Fitting a single tuned filter model to the data at each station alleviated this problem. A major impact on future experiments was the realization that some data should always be taken at the maximum sampling rate (without digital filtering) in order to facilitate the modeling.

B. Second Experiment

The second short-baseline experiment was performed on June 2, 1976, between DSS 11 and DSS 12, both at Goldstone. The objective of this experiment was to gain experience in using the wideband data acquisition system with several different receiving systems of different bandwidths. A simultaneous experiment was conducted by J. Fanselow and J. B. Thomas of the JPL Tracking and Orbit Determination Section, using the 48-kb/s computer-based recording system developed by D. S. Robertson and A. H. Legg of the Weapons Research Establishment, Australia (Ref. 15), and using the technique of bandwidth synthesis (Refs. 5, 6, 7, 8) to achieve wide effective bandwidths.

Three different receiver configurations were used in the June 2 experiments:

(1) Block III Receiver. This configuration was essentially the same as in the Dec. 14, 1975, experiment, except that the non-AGC'd 50-MHz amplifier outputs were used, whereas the AGC'd TLM-C channel outputs had been used previously. Hewlett-Packard 5100 frequency synthesizers were used in the local oscillator generation as before.

(2) Wideband. This configuration utilized a pair of wideband open-loop receivers developed for VLBI by the JPL Tracking and Orbit Determination Section. The S-band local oscillator in these receivers is generated by direct multiplication of the 5-MHz frequency standard output.

(3) 10-MHz Bandwidth. This configuration utilized the wideband receivers, as in (2), but filtered the IF outputs to 50 ± 5 MHz using multiple-pole tuned filters, achieving nearly rectangular passbands.

The passband shapes for the wideband receivers are shown in Fig. 3 and for the Block III receiver in Fig. 4. The curves shown are not measured power spectral densities but are the shapes of multi-pole tuned filter approximations to the passbands. These tuned filter approximations were determined by fitting filter models to the observed autocorrelation functions. The models were used to obtain an approximation to the cross-correlation function of the two receiving systems, which was in turn used by the processing program. The configurations using the 10-MHz filter were modeled as ideal rectangular filters with passbands of 49.826 ± 5.383 MHz at DSS 11, and 49.740 ± 5.474 MHz at DSS 12.

The measured clock offsets for 27 observations of three radio sources were typically −1.5 μs for $T_{12} - T_{11}$, compared to the a priori value of −4 μs determined by the microwave links. Figure 5 shows the residual clock estimates for all cases, relative to a straight line fit between all cases having the wideband configuration. The system configurations are indicated for each observation, and the error bars are sample standard deviations using all of the data for each observation. The differences in sample standard deviations are primarily due to different source strengths, receiver bandwidths, and digital filter bandwidths. Also, the fourth observation was for only 3 min, due to low source elevation, whereas the others were all for 9 min.

The results are surprisingly consistent from one receiver configuration to another, considering that the different station delays were not calibrated. For the wideband receiver, the results for different filter bandwidths differ by as much as 7 ns. This could be due to differences in average group delays in different portions of the overall system passbands and/or to errors in modeling the cross-correlation function. For the narrower-bandwidth receiver configurations, the variations in time delay estimates with digital filter bandwidth are obscured by the larger sample deviations and by drifts due to the oscillators or temperature changes.

Specific results for the wideband receiver configuration are shown in Fig. 6. The observed time delay resolution (1-σ sample deviation) is shown as a function of inverse digital filter bandwidth for three observations of source 3C273. The sample deviations are per 0.75 Mb of data. Assuming the bandwidth to be determined entirely by the digital filter, the theoretical standard deviations of time delay estimate are directly proportional to inverse system bandwidth, so that the points would fall close to the straight line, within experimental error. The results indicate that the receiving system bandwidths have some effect when the 25-MHz digital filters are used, and when there is no filtering. With this strong source, a resolution of 0.8 ns was achieved with only 0.75 Mb of data.

The Block III receiver and the 10-MHz filter configuration realized the time delay resolutions shown in Fig. 7 for various digital filter bandwidths. The resolutions are approximately proportional to inverse digital filter bandwidth, even when the nominal filter bandwidth was 12.5 MHz, which is wider than the receiver bandwidths. This indicates that, for these receiver passbands, best results are obtained when the digital filter bandwidth is somewhat wider than the receiver bandwidths. The sample deviations are better for the 10-MHz filter than for the Block III receiver. For both receiver configurations, resolutions of better than 5 ns were achieved for the normalized data size of 0.75 Mb, which corresponds to subnanosecond resolution for the entire 30 Mb per observation.

C. Long-Baseline Experiment

The first long-baseline experiment was performed on October 14, 1976, using DSS 14 at Goldstone and DSS 43 in Australia. The primary objectives were to demonstrate that the data acquisition system could be installed and operated properly by station personnel, that the system operates properly with Block IV receivers, and that the data acquisition hardware and software and the processing software perform properly for long baselines. These objectives were all achieved with an experiment scheduled for less than 3 h, including the time required to install and remove the data acquisition systems.

Figure 8 shows the modeled signal passbands as observed at the 55-MHz IF amplifier outputs on the Block IV receivers. With proper wideband tuning of the RF maser amplifiers, the passbands at this point in the system should be dominated by the receiver three-pole Chebychev filters with 3-dB bandwidths of ±18 MHz. This was clearly not the case for this experiment. The passband was especially bad at DSS 14, where it was necessary to use a traveling wave maser having a narrower bandwidth than is usually available.

Five successful 9-min observations were made, each using three different digital filter bandwidths: 5 MHz, 27.5 MHz, and unfiltered. The clock offset estimates for the five observations, one of CTA 26 and four of NRAO190, are shown in Fig. 9 for the 27.5-MHz and the unfiltered configurations. The clock offset estimates are in the range of $T_{43} - T_{14}$ = 0.64 to 0.71 μs, which is within 3 μs of the a priori offset determined from the microwave link estimate of $T_{14} - T_{DSN}$ = −4 μs, and the estimate of $T_{43} - T_{DSN}$ = −2 μs from the DSN operational time sync system, using the moon bounce technique. The discrepancy of less than 3 μs is within the approximate 5-μs accuracy of the moon bounce system (Refs. 16, 17).

The slopes of the clock offset estimates versus time in Fig. 9 were determined from the fringe frequency estimates. For the four observations of NRAO190, the slopes are in good agreement with the changes in clock offset estimates with time. Changes both in the slopes and in the clock offset estimates, and the differences between the two sources, can be attributed to various effects, including oscillator offsets and instabilities, source position errors, propagation medium delays, and uncertainty in UT1. The assumed source positions of date were RA = 70.021958 deg, dec = −0.388889 deg for NRAO190, and RA = 54.245708 deg, dec = −1.937944 deg for CTA 26. These could be in error either due to the catalog position used or to inaccuracies in the precession program. The assumed value for UT1-UTC was −92.2 ms.

Sample standard deviations of clock offset estimate were determined for all cases by dividing the data into 18 independent 10-s intervals. Normalized to 10^6 bits, the 10-MHz, 27.5-MHz, and unfiltered cases achieved sample deviations of 5.37, 1.41, and 1.33 ns for CTA 26, and 12.68, 2.67, and 2.24 ns for NRAO190. The deviations improved almost as inverse bandwidth as the digital filter was widened from 5 to 27.5 MHz, but there was little improvement from 27.5 MHz to the unfiltered cases. This seems to be in line with the passband shape at DSS 14, which is about 22 MHz wide at the 6-dB points. It would not have been surprising if the deviations had been higher for the unfiltered cases than for the 27.5-MHz filter. When the full 36-MHz bandwidth of the Block IV 55-MHz output is realized, the unfiltered case will certainly be best.

The overall resolution for each observation was better than 1 ns for both the 27.5-MHz and the unfiltered cases, with a total of about 10^7 bits of data.

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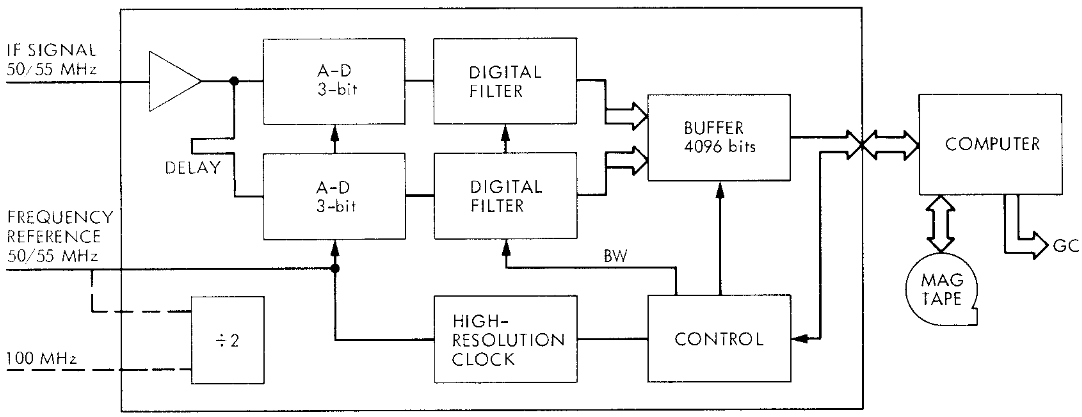

Fig. 1. Wideband digital data acquisition system block diagram

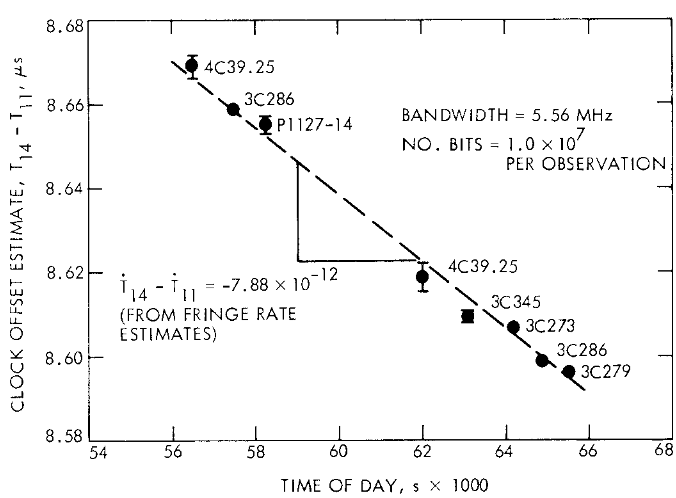

Fig. 2. Clock offset estimates for Dec. 14, 1975, with 1-σ sample deviations

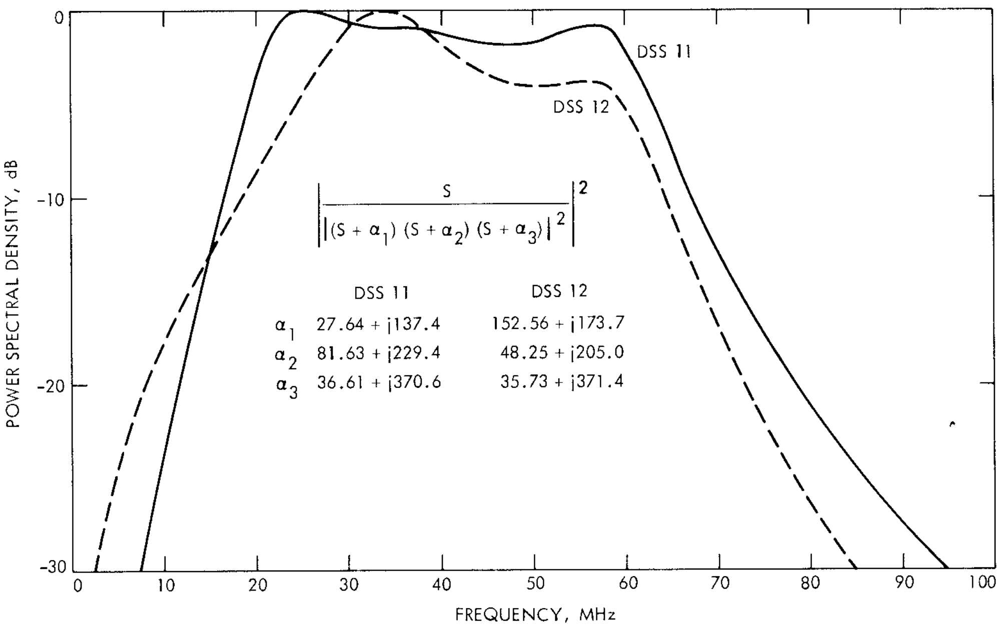

Fig. 3. Modeled receiver passbands, wideband receiver (June 2, 1976)

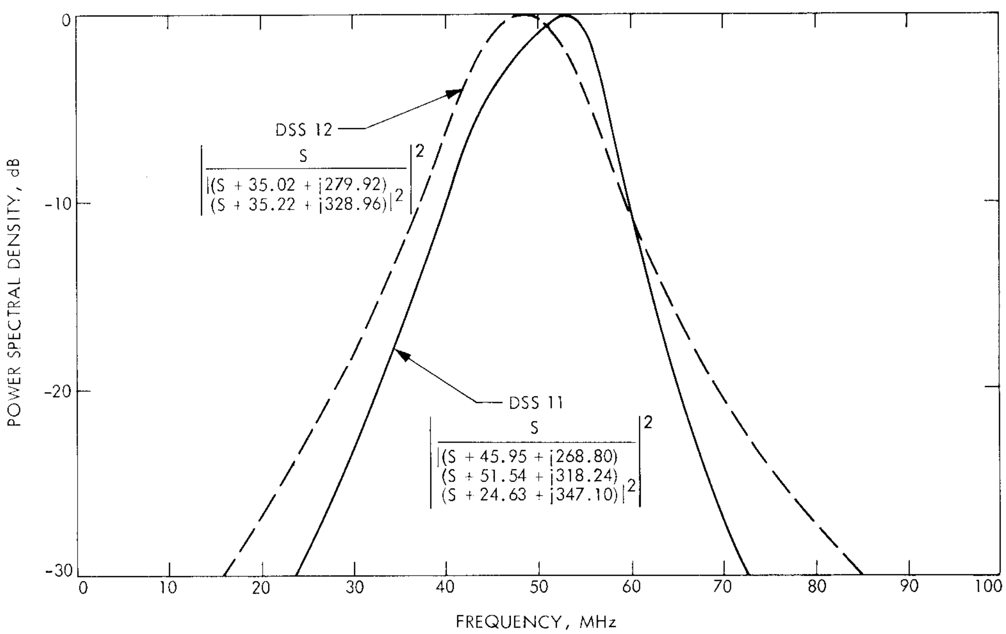

Fig. 4. Modeled receiver passbands, Block III receivers (June 2, 1976)

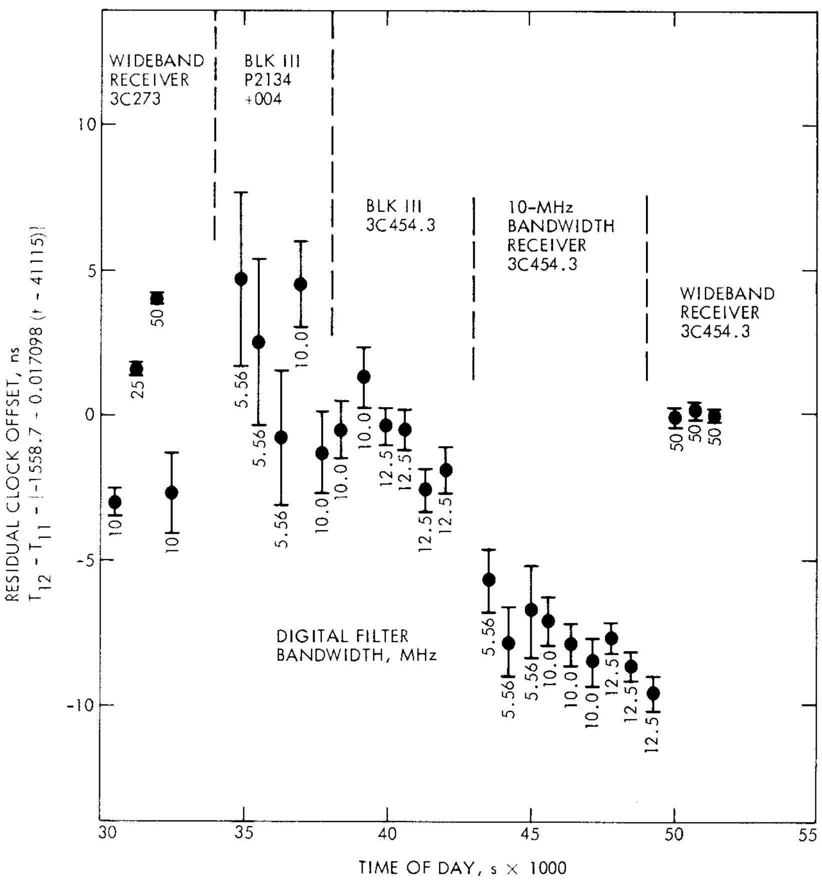

Fig. 5. Residual clock offset estimates for June 2, 1976

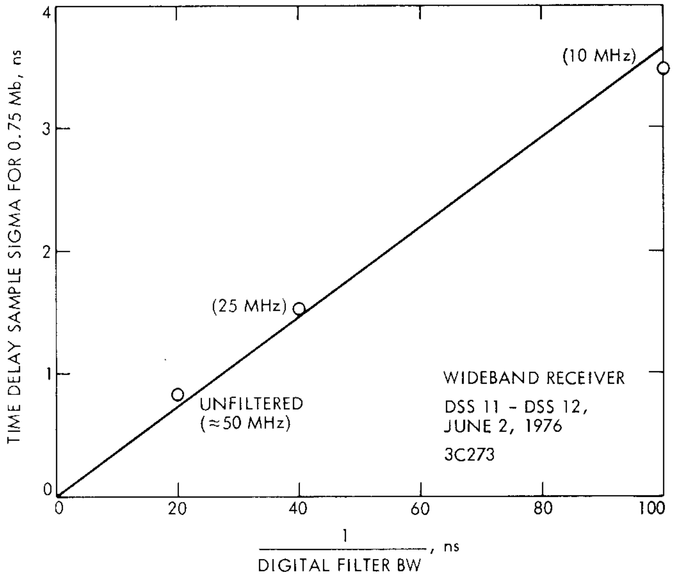

Fig. 6. Time delay resolution vs. bandwidth, wideband receiver

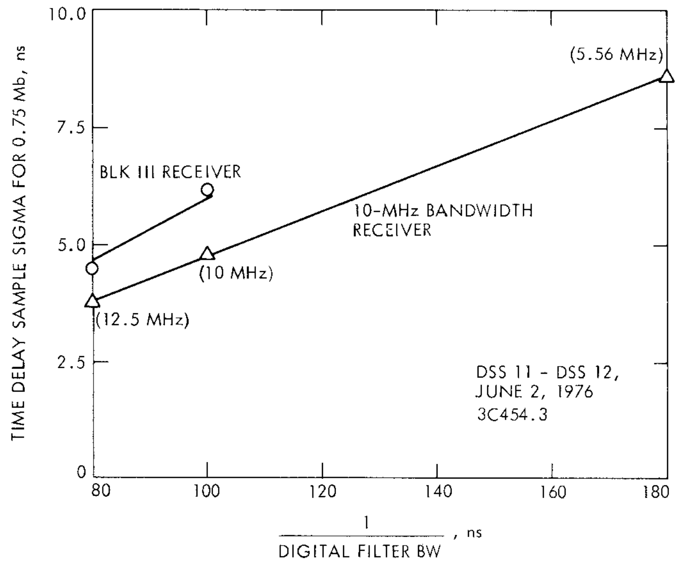

Fig. 7. Time delay resolution vs. bandwidth, Block III receivers

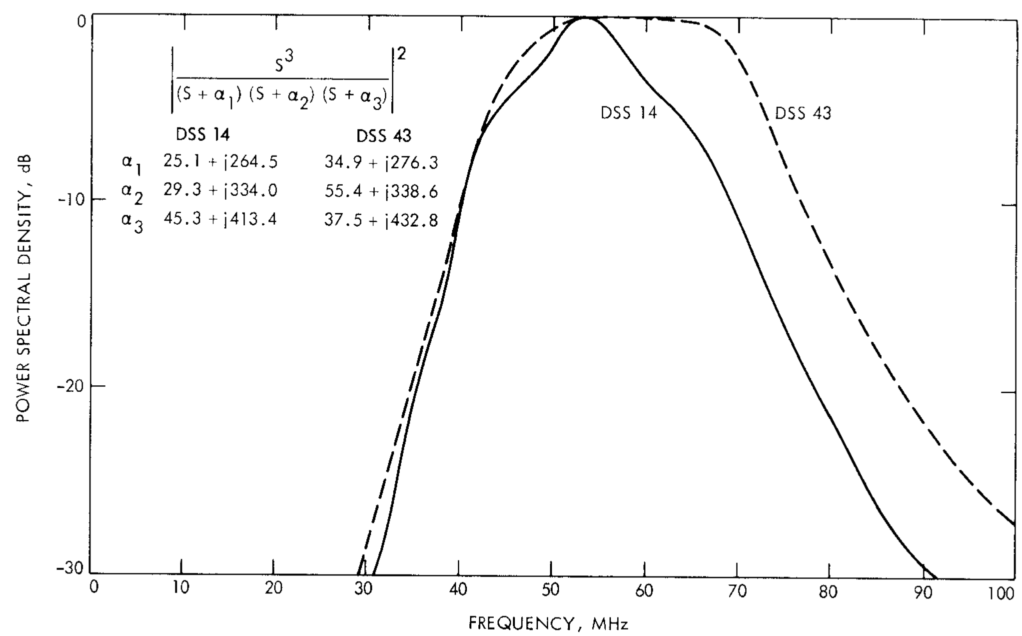

Fig. 8. Modeled receiver passbands, Block IV receivers (Oct. 14, 1976)

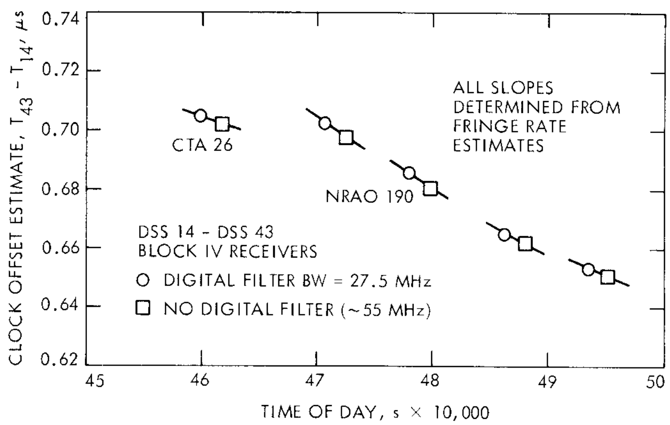

Fig. 9. Clock offset estimates for Oct. 14, 1976