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CONTINUOUS, MULTI-CHANNEL, COMMON-VIEW, L1-GPS TIME-COMPARISON OVER A 4,000 km BASELINE.

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Abstract

We are investigating a method of time comparison described as "Advanced Common-View GPS" or GPS-ACV. This is a technique that uses the largest possible number of observations on all satellites in common-view to average short-term noise and reduce the effect of errors. The goal is to make optimum use of all degrees of freedom afforded by the data. We have recently tested the ACV method over a 4,000 km baseline using inexpensive, single-frequency, modular GPS receivers. The results indicate that a measurement noise of less than 1 nanosecond can be obtained for averaging times of 1 and 2 days. The equivalent uncertainty for frequency transfer is below 10^{-14}

1. Introduction

The coordination of time-scales at a national and international level is increasingly important in communication, navigation and science. The greatest accuracies are currently required for VLBI, spacecraft navigation, and geodesy, where an accuracy of better than one nanosecond is desirable. The same accuracy is necessary for the construction of the international time-scale UTC. The current proposal to use the Global Positioning System (GPS) for aircraft navigation and landing implies a requirement for time coordination with an accuracy approaching a few nanoseconds on a continental scale. Some cellular telephone systems also require precise, wide-area, time coordination.

Methods of comparing time-scales maintained by separated clocks can be characterized by accuracy, stability, and processing time. Accuracy is needed for comparison with UTC, and processing time is of secondary importance. For comparing the frequencies of very stable clocks, stability is most important since frequency differences are obtained by subtracting time differences. For synchronizing less stable clocks, processing time must be kept short.

Since its introduction, The Global Positioning System has been used as an economical, world-wide, means for time-scale dissemination, and time comparison [1]. Most measurements by civil users employ "Coarse/Acquisition" (C/A) code ranging at the L1 frequency, and are now subject to the noise associated with "Selective Availability" (SA). For precise and accurate time comparison the "common-view" measurement technique is used [2]. This method is not directly degraded by the presence of SA in the form of satellite clock jitter. Over intercontinental distances, accurate time comparison requires local measurements of ionospheric dispersion, and post-processing of the results using filtered precise ephemerides [3]. Dual frequency receivers can now measure the ionosphere even in the presence of "Anti-Spoofing" (AS) [4]. The highest accuracy in time-coordination has been achieved by comprehensive post-processing of the code and carrier data from large arrays of geodetic receivers using complex algorithms. The algorithms model the many state-variables and all important errors in the GPS system, and the technique has demonstrated a time-transfer accuracy below 1 nanosecond [5,6].

The GPS system has reached "Full Operation Capability" (FOC), and as many as 12 satellites may be in view at once from a given location. Various techniques can now be used to obtain improved accuracy using simple observations with modest equipment. The simultaneous tracking of several satellites reduces SA noise, potentially reduces ephemeris and ionosphere errors by averaging, and provides important self-consistency information. Multi-channel, single-frequency, time receivers are now available in stand-alone and modular form. Some of these receivers contain software to detect and suppress the measurements from any satellite that shows a large pseudo-range error.

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One multi-satellite technique, which has been described as "Enhanced GPS" or EGPS, consists of using a suitable receiver to obtain an average time solution including several satellites simultaneously [7,8]. Ideally, the receiver uses the accurately-known antenna coordinates, increasing by 3 the number of satellites from which data can be averaged to obtain the time solution. The resulting time output is related to the GPS timescale, optionally corrected to UTC(USNO), and is modulated in the short term by noise resulting from SA. The rms deviation is about 75 ns divided by the square-root of the number of satellites used in the solution. If a stable local oscillator is used, this noise can be filtered, reducing the overall variance at short times 7,9]. Averaging over 1 day would lead to a variance of between 1 and 2 ns if no other sources of noise were present. This technique can also be used in a "quasi-common-view" mode [7], with further noise reduction.

We are currently investigating another multi-satellite technique of time-comparison which we have described as "Advanced Common View GPS" or GPS-ACV [10]. This is a method that uses the largest possible number of observations on all satellites in common-view to average short-term noise, and minimize the effects of pseudorange errors. The goal is to make optimum use of all degrees of freedom provided by the data. Readings must be coordinated between synchronization sites to obtain time differences, but this can be done very quickly using Internet. The technique has the potential for making time-comparisons in near real-time. Accurate time-transfer with short processing times would be particularly useful for wide-area synchronization of clocks having moderate stability. The method, and preliminary results obtained over a baseline of 4,000 km will be presented in this paper. Some preliminary results taken over shorter baselines have already been reported [10].

2. Description of the ACV Method

In the ACV method, a multi-channel receiver is used to make continuous pseudorange observations on all satellites satisfying a minimum elevation "Mask" angle. The same measurements are made at all locations making time comparisons. To obtain the time difference between two sites, a subtraction is made "off line" including only those satellites in common-view. Since all useful satellites are logged at all locations at all times, no observing schedule is required. The receivers operate in a "Position Fixed" mode, in which the measured pseudorange is compared with that calculated using the data in the navigation message and the known antenna coordinates, giving a pseudorange residual for each satellite being tracked. The receiver clock bias is removed either by synchronizing the receiver clock with the local time-scale, or by comparing the receiver 1 pps output with the local clock by means of a time-interval counter. To obtain the greatest possible accuracy, the measured ionospheric delay, the antenna and cable delays, and the receiver delay are subtracted when the pseudorange residuals are calculated. For single frequency receivers, the standard Single-Frequency ionosphere correction is calculated from the parameters in the navigation message, and may be included. The pseudorange residuals output by the receiver are instantaneous estimates of the time difference between the GPS clock and the local clock. They are low-pass filtered to reduce the data rate, and logged.

In order to perform a time comparison, two stations exchange data. The data for a given epoch is processed by subtracting the readings satellite by satellite. The pseudorange residual differences for those satellites that have satisfactory signals, and appear in both sets of data, are averaged to form the estimated time-scale difference at the selected epoch. The rms of the readings is an important indicator of consistency. The use of the Internet to exchange data allows a time comparison to be performed in a few seconds. If longer processing times are acceptable, larger files can be exchanged less frequently, and the differences averaged over time. Long filter time-constants could be used to reduce the data rate if the same value were used at all stations, and comparison with other measurements were not required. If the filter were too slow, data would be lost because the filter settling time would encroach on the length of a satellite pass.

In the experiments to be described, 8-channel, single-frequency receivers were used. The receivers calculated raw pseudorange residuals and clock biases in meters, together with flags indicating the status of each receiver channel. An external time-interval counter measured the difference between the local clock and the receiver clock, using the receiver 1 pps pulse output. An external computer scaled the pseudorange residuals, and combined them with the counter output. This computer then low-pass filtered the data to a manageable bandwidth. The properties of the filter used were chosen to track SA without significant errors, allowing the data to be compared with conventional common-view measurements. The filter also rejected any data which differed by more than 100 ns from that predicted by extrapolation from previous points. The computer generated a channel status flag which was set whenever a given channel had been tracking data continuously for the settling time of the filter. Every ten seconds the filtered pseudorange residuals, the channel status flags, and a time-stamp accurate to one second, were output over a serial data link to a file server. The data records had a maximum length of 135 bytes. All sites logged data at UTC times modulo 10 seconds.

The advantages of this method include fast response, simplicity, flexibility, modest equipment requirements, and compatibility with existing common-view protocols. The technique is quite easily automated, and is suitable for real-time replication of time-scales over moderately wide areas.

3. Sources of Error

The ACV method is sensitive to pseudorange errors corresponding to differences between the actual orbit parameters and those output by the satellites in the Navigation Message. It will be assumed that the positions of the ground stations are accurate. Because the method uses common-view observations, satellite clock errors are not significant. The clock frequency perturbations associated with SA can, however, have peak amplitudes of several parts in 10^{-9}. To reduce SA errors below 1 ns, it is therefore necessary to synchronize measurements to a fraction of a second. This is generally not difficult if the receivers generate their outputs coherently with the GPS time-scale.

Satellite position errors affect the measurements to a degree depending in a complicated manner on the spatial relationship between the radius vectors to the satellite and the baseline vector joining the time comparison sites[2]. In the worst case, for a satellite overhead, the time difference error resulting from an orbit error of 1 m in the direction parallel to a 4,000 km baseline is 0.7 ns. In the ACV method, each satellite can be observed over some portion of its orbit, and it may be assumed that this error will be somewhat diluted by averaging. In all cases the effect of satellite ephemeris errors increases with baseline. A statistical model of the ephemeris errors in the GPS system can be accumulated by comparing the Navigation Message data with precise post-determined orbits. One such study has given root-sum-of-squares errors between 2 and 4 meters [11]. In general, since only one error direction introduces timing error, one might be justified in taking 1.2 to 2.4 m as representative. In view of the spatial factors given above, one might thus estimate a typical single-track rms time error of about 1.5 ns for a baseline of 4,000 km. Since position errors should not be correlated from satellite to satellite, and many satellites appear in common view each day, the accuracy should increase with averaging over time

Time-dependent errors due to multipath propagation will be present. These can be minimized by proper selection and siting of antennas, and by the use of a large elevation mask angle. Estimation of the magnitude of multipath errors is speculative, but the extensive averaging involved in the ACV technique should minimize their overall effect.

GPS code pseudorange measurements contain the group delay caused by free electrons in the ionosphere. The local density of electrons is not well-modeled, and varies with solar activity, position on the Earth's surface, season, and time of day. The group delay is proportional to the free electron density integrated along the slant path length through the ionosphere to the satellite. Two-frequency receivers can measure this effect and allow for it, but single frequency receivers are directly affected. The navigation message contains 8 parameters that can be used in the receiver to construct a real-time model of the ionosphere. The parameters are calculated by the GPS Operational Control Segment from measured solar flux data, and uploaded fairly frequently. Because of the complex behavior of the ionosphere and the limitations of the model, the use of the calculated data in the navigation message does not eliminate the ionospheric delay. It is predicted that ionosphere errors will be reduced by about a factor of 2 by using the model [12]. A significant feature of the model is that its use appears to reduce the bias that would result from uncorrected ionosphere errors [13]. It has also been pointed out that the current model does not have sufficient dynamic range to follow the expected extrema in solar activity [13].

In the ACV method using single-frequency receivers, uncompensated ionosphere delays will be a major source of error. Estimation of the magnitude of the errors is difficult. The effects are most significant at low satellite elevations, and can be reduced by using a high mask angle. The effects should also be reduced by common-view, particularly when a satellite is visible first at one site, and last at the other. This averaging effect is reduced by the fact that the ionospheric effect contains a North-South asymmetry. With increasing baseline, the spatial and temporal coherence of the delays becomes smaller and the use of a high mask angle becomes impossible. The electron density peaks at about 1400 hrs local time, and measurements at night are therefore affected least. The length of good observing time is obviously reduced with the separation of the sites in longitude. A study [13] has indicated that, for mid latitudes, during periods of high solar activity, the night-time ionosphere uncorrected errors will remain below 3m for 90% of the time. In quiet years the average effect might be smaller by a factor of about 3. The result of using ACV at large baselines might be a further reduction by a factor of 2, suggesting a day-to-day variation between 1 and 3 nanoseconds for night-time observations in undisturbed periods. It has recently been suggested that iono-

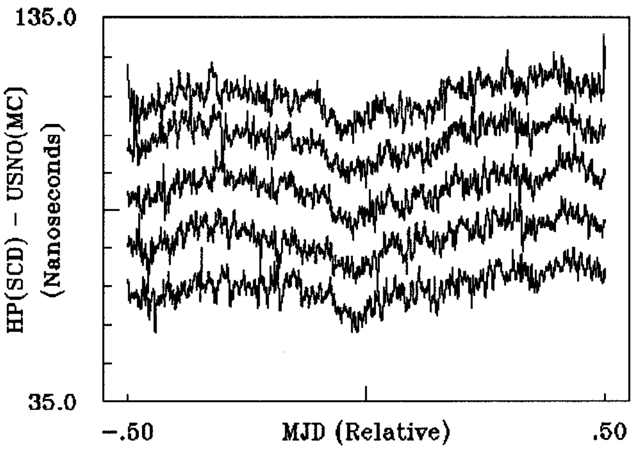

Figure 1. Alternate one-day segments of ACV time-difference data taken over a 4,000 km E-W baseline. The traces are separated by exactly 2 days. The vertical separation of the traces is due to an offset of 7.2 10^{-14} in the SCD clock. An elevation mask angle of 15 degrees was used, and the Single-Frequency ionospheric correction was turned on. The data has been low-pass filtered with a time-constant of 100 seconds.

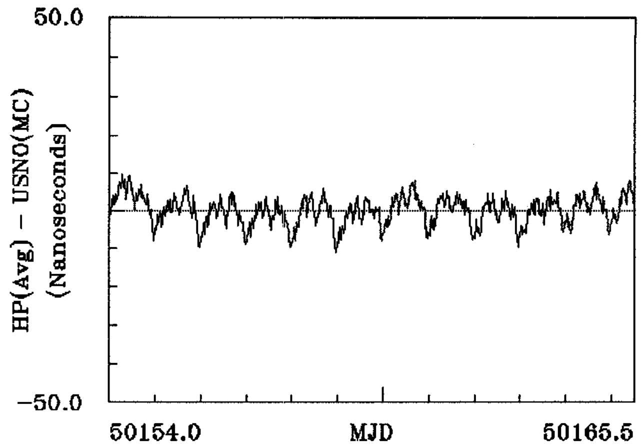

Figure 2. Average time difference from 11.5 days of continuous ACV data taken over a 4,000 km E-W baseline. An elevation mask angle of 15 degrees was used, and the Single-Frequency ionospheric correction was turned on. The raw data has been decimated by a factor of 135 to give 64 points per day. and a frequency offset of 5.2 10^{-14} has been removed.

spheric delays might be estimated in real-time by careful measurements with single-frequency receivers [14,15]

The GPS system is extremely complicated, and errors cannot always be expected to be statistically distributed. Redundancy should be exploited as much as possible, and robust methods should be used to identify and remove outliers.

4. Experiments and Results

The measurements to be discussed were made using modular, 8-channel, single-frequency GPS receivers equipped with active microstrip patch antennas. The same equipment and software was used at each of three locations: Hewlett Packard Laboratories (HPL); Hewlett Packard Santa Clara Division (SCD); and United States Naval Observatory (USNO). The antenna coordinates at HPL and SCD were determined by averaging the GPS multi-satellite position solution for several weeks. The position of the USNO antenna was accurately known from prior surveys.

The reference clocks at HPL and SCD consisted of ensembles of, respectively, two and three HP 5071A cesium standards, and master clock II was used at USNO. Data was taken at 10 second intervals and exchanged by Internet. The data for one day of observations at one site totaled about 920 kilobytes.

Figure 1 shows 5 one-day segments of ACV time-difference data taken between HP(SCD) and USNO. Alternate one day segments spaced by exactly two solar days are plotted. The receivers operated with an elevation mask angle of 15 degrees, and the single-frequency ionosphere correction was enabled. Each segment contains common-view data from 24 satellites and includes 17 single-satellite passes with a duration exceeding 3 hours. The average number of satellites in common view was 3.75. The vertical separation of the plotted traces results from a 7.2 10-14 frequency offset at SCD with respect to USNO.

The data plotted in Figure 1 shows short-term noise with distinctive features that appear earlier each two days by about 8 minutes, the difference between sidereal and solar time. These are presumed to be due to the changing constellation in view, and multipath effects. This noise is approximately 10 nanoseconds peak-to-peak with the 100 second filter time-constant used to plot the data.

The data also shows a one cycle per day periodic modulation of the time difference which will be discussed in more detail later.

Figure 2 shows 11.5 days of continuous time-difference data comparing a weighted average of the HPL and SCD time-scales with USNO Master clock II. The baseline for these observations was 4000 km in a nearly East-West direction. The receivers operated with an elevation mask angle of 15 degrees, and the Single-Frequency ionosphere

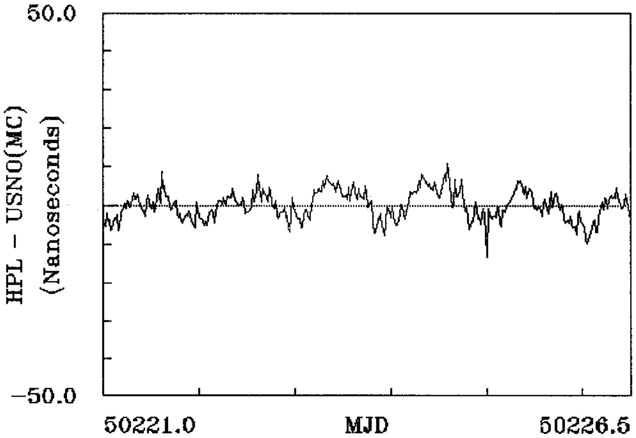

Figure 3. Average time difference from 5.5 days of ACV data taken over a 4,000 km E-W baseline. An elevation mask angle of 35 degrees was used, and the Single-Frequency ionospheric correction was turned on. The raw data was decimated by a factor of 135 to give 64 points per day. The time differences have been corrected for steering of the HPL clock, and the average frequency difference has been subtracted.

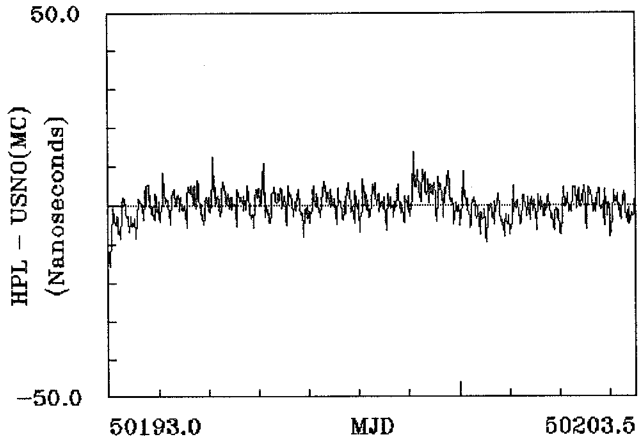

Figure 4. Average time difference from 10.5 days of ACV data taken over a 4,000 km E-W baseline. An elevation mask angle of 15 degrees was used, and the Single-Frequency ionospheric correction was turned off. The raw data was decimated by a factor of 135 to give 64 points per day.

correction was enabled. The raw data has been decimated by a factor of 135, giving 64 points per day. The average number of satellites in common view was 3.75, so that the number of 1 second observations contributing to each averaged time-difference exceeded 5,000.

The decimated data again clearly shows a one cycle per day modulation. The values of rms time deviation (TDEV) given by this data at averaging times of 1 and 2 days are 0.7 ns and 1 ns, respectively. When the estimated noise due to the clocks at SCD and HPL is allowed for, values of measurement noise of 0.5 ns and 0.8 ns are obtained. These values are unchanged by a constant diurnal effect.

Figure 3 shows 5.5 days of continuous time-difference data comparing HPL against USNO. The elevation mask angle was set to 35 degrees at both sites, reducing the average number of satellites in common view to about 2, and giving about 16 single satellite passes exceeding 2.5 hours in duration per day. The Single-Frequency ionosphere correction was enabled. The data has been corrected for steering of the HPL clock ensemble, and the average frequency offset has been removed. The value of time deviation given by this data at an averaging time of 1 day is 0.7 ns.

An obvious diurnal effect is again present. Fourier analysis shows that the phase of the diurnal effect referred to UTC is approximately the same for the data shown in figures 2 and 3 although the difference between Solar and Sidereal time has changed by more than 4 hours. This suggests that the effect is not due to receiver coordinate errors. Although the number of satellites in common view has been reduced by increasing the mask angle, the short-term noise level is comparable for the data shown figures 2 and 3.

In order to investigate the influence of the Single-Frequency ionosphere model on the diurnal effect, measurements were made with the correction turned off. Figure 4 shows 10.5 days of continuous time-difference data comparing HPL against USNO. The mask angle was again set to 15 degrees, and the ionosphere correction was turned off at both sites. The data has been corrected for steering of the HPL clock ensemble and an average frequency offset has been removed.

It is clear that turning off the ionosphere model reduced the amplitude of the diurnal effect. Fourier analysis shows that the amplitude of the one cycle per day component was reduced by a factor of more than 3. Data gathered by another receiver at USNO shows that the magnitude of the ionosphere correction given by the standard model using the data in the navigation message was approximately constant over the period of the measurements shown in figures 2, 3 and 4, and it is thus improbable that the reduction was caused by a change in the actual ionospheric delay

When TDEV values are calculated for the data in figure 4, It is apparent that the common-view, short-term, noise is increased by about 60% when the ionosphere correction is not used.

Table 1:

Data	Amplitude of Diurnal effect (ns)	UTC Time of Maximum	T-Dev, 1 day (ns)	T-Dev, 1 day (ns)	RMS deviation (ns)
A	3.4	11:34	0.7 (0.46)	1.0 (0.64)	5.0
B	3.5	12:37	0.8 (0.72)	1.2 (1.0)	5.1
C	3.8	12:41	0.7 (0.72)	-	4.1
D	0.92	16:21	1.3 (0.72)	1.4 (1.0)	7.9

Numerical results calculated from the ACV data taken over the 4,000 km baseline. A: the data shown in figure 2. B: 12 days of continuous data taken between HPL and USNO with ion correction enabled and a mask angle 15 degrees. C: the data plotted in figure 3. D: the data plotted in figure 4. The diurnal effect is modeled as a Cosine with 1 day period. The data in brackets in the T-Var columns is the expected total noise due to the clock ensembles in use at HPL and SCD, with appropriate allowance for ensembling.

Table 1 summarizes the data obtained from time-difference measurements made over the 4,000 km baseline. The table contains the time deviations calculated for averaging times of 1 and 2 days, and the estimated contribution of the local clocks to each result. The table contains the calculated amplitude of the fundamental component of the one cycle per day noise, and its phase with respect to UTC. Also given in the table is a typical daily average rms deviation of the individual satellite measurements contributing to the average common-view time difference.

5. Discussion

The 4,000 km baseline measurements described above demonstrate the potential of the ACV technique, and the extremely small measurement noise of the C/A code receivers. The time-deviation typically observed with 4 satellites in common view is 1.0 ns at an averaging time of 100 seconds. At short times there will be no correlation between satellites, so that 2 ns would be observed for a single channel. This corresponds to an rms correlator noise of 1.4 ns for one channel of a single receiver averaged for 100 seconds. The receivers used employ carrier phase smoothing of the correlator output with a maximum time-constant of 128 seconds. This result shows how effective current receivers are, even when operating on the 1 microsecond chip-length C/A code.

The diagnostic potential of the ACV method is shown by the high time-resolution traces in figure 1. The time-difference given by each satellite in common-view can be plotted separately, allowing pseudorange, antenna coordinate, and ionosphere errors to be investigated. Table 1 shows that the rms deviation between the time-differences for the satellites in common view is about 5 ns with the ionosphere correction enabled. This is an estimate of the total of pseudorange errors and contributions from the spatial part of the unmodelled ionosphere effect.

The long-baseline data shows a diurnal effect with a peak-to-peak amplitude of up to 15 ns. The phase of this effect has been found to remain constant with respect to UTC over at least 6 months, showing that it is not related to the position of the satellite constellation. Although the receivers and antennas are sensitive to temperature, the magnitude of the diurnal effect, and its constancy over time, make environmental sensitivity an unlikely explanation. The error appears to result from the interaction of the real ionospheric delay, the Single-Frequency ionosphere model (as implemented in the receivers used), and the ACV measurement technique. This conclusion is supported by the distinct change when the ionosphere correction is disabled. We have recently also observed changes in the diurnal effect synchronized with changes in the ionosphere parameters in the navigation message.

The amplitude of the diurnal effect, and its phase referred to UTC, were quite constant over a period of 60 days for a given set of observing conditions. The time deviations calculated from the data show that the ACV technique is capable of a precision of significantly better that 1 ns for averaging times of 1 and 2 days. The measurements of the instrumental noise level were limited by the stability of the available clocks. For short-term, relative time delay measurements, very low noise levels could be obtained by adaptive or other forms of filtering. It should be noted that the measurements discussed in this paper were taken near the seasonal minimum in a year close to the lowest Solar activity.

To carry out long-term accurate time-transfer it will be necessary to understand the origin of the diurnal effect and predict the bias, if any, associated with it. This diurnal error may be significant in some current common-view measurement systems.

Conclusions

The results that we have obtained demonstrate the potential of the ACV technique for precise time and frequency comparison over moderate baselines. Advantages of the method are simplicity, low noise, and almost real-time results. It will be important to understand the cause of the diurnal effect observed in order to model it. The modular GPS receivers used were found to have very low correlator noise, but temperature effects could usefully be reduced.

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