GPS CLOCKS IN THE EVN;
TOWARD BLIND CORRELATION

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Introduction

The aim of this report is to show how we can benefit in the EVN from consistent recording of GPS readouts. The goal is to obtain sufficient a–priori knowledge of the long term behavior of the maser clocks around the network to enable "blind" correlation. By this is meant that at the correlator it will be possible to start correlation without doing a clock search first. Such information will also help to enable correlation of large bandwidth with low spectral resolution and long integration times per visibility. Both these features are important for running a correlator with a large number of stations. First, to ensure efficient use of the correlator and, second, to limit the output volume the user has to deal with. Finally, getting as accurate knowledge as possible of all the components in our system, reduces the amount of calibration on astronomical sources needed to process the data. This will make VLBI a simpler and more accurate technique.

This document describes some tests I performed on a limited amount of GPS data from 4 EVN stations. The GPS data is used to monitor the long term behavior of the hydrogen masers clocks. I compared the drifts, predicted with this method, to the results of fringe searching at two correlators. The comparison data were taken from correlator logs, in which the results of previous fringe searches were stored. These are of a rather arbitrary accuracy, but still the comparison shows that the GPS data around the EVN can be used to predict delay and rate with a relevant accuracy.

After the discussion of the measurements, Appendix A gives a file format and measurement method, proposed to accommodate consistent logging around the EVN. This proposal was formulated in collaboration with Tony Foley (WSRT) and Jon Romney (NRAO) and published by e–mail in April 1995. We are aiming to implement the interfaces for this before the start of 1996.

The plots of clock drift and correlator results may of interest for several other purposes. For completeness I attach in Appendix B the correlator results for EVN stations for which I had no or little GPS data available.

Measurements

Data were made available after the 1994 TWG meeting by a number of stations. The range of data and the frequency of the readouts are given in Table 1. The measurements were not taken with the current purpose in mind. In some cases the history of the GPS versus the local maser clocks was retrieved with some difficulties. Furthermore, different stations had different policies about how often to record the data, some of these clearly not optimal.

Table 1. List of available GPS data

Station	Data available		Readouts	Number of GPS
	start	end		receivers
Jodrell Bank	Aug 1 1994	Jan 31 1995	1/hour	2
Medicina	Jan 1 1991	Dec 31 1994	1/day, 5 values	1
Metsahovi	Jan 1 1993	current	1/10 min	2
Onsala	Jan 1 1994	Dec 31 1994	1/day	1

The GPS data from these station were transformed to a common data format. In the process some filtering was applied. Data with very high values were discarded and values close to a second were reduced to small negative values. These values arise because the stations usually record the difference between the station clock 1 pps and the GPS.

The sign of the GPS/formatter offset is a bit confusing, especially because different correlators use different conventions. However, all GPS timing information that I have seen, including the VLBA GPS readouts, come with the same convention. Measurements of GPS/formatter result in a negative number when the maser clock is slow. Extra cabling from the telescope to the formatter in this convention should cause the number to become larger (as we find below). For the Bonn correlator these numbers can be used directly to insert the right clock offsets. In the VLBA correlator a sign flip is necessary. All the plots shown in this document are shown in the latter, i.e. "flipped" convention. Note that the convention of AIPS is such that residual values found should be added to the station clock table at the VLBA correlator to make the delays come out closer to zero. For the Bonn station clock table they should be subtracted.

The data were further processed by fitting linear models of delay and rate in a running window, yielding fit values for every day, which are not completely independent. A typical window size is 7 days, but where data was taken more frequently than daily, smaller windows were used. The fits also yield a formal error for the delay and rate. For stretches in which the error in delay was more than 2 μs or the rate error was larger than 5 ps/s, the data was flagged. In the comparison with the correlator results, the nearest previous, acceptable result of the fit was used, provided is was obtained within 20 days.

Correlators

The GPS measurements are compared against values measured at the correlator, primarily these obtained at the VLBA correlator. These experiments have the advantage that they are correlated with respect to VLBA antennas with accurately monitored clocks. After fringe searches the results are usually stored in an experiment specific table which is used to run the correlator for that project. The information from these files was retrieved and stored in the same format as the GPS data. Typically fringe searches are done on a limited part of the data and only with the goal to get usable clocks. This limits the accuracy of the values. In addition some confusing entries were encountered in the correlator files, where a station may have failed or show erroneous results. Finally, some results, notably on the rates, may depend heavily on the correlator model, including source and antenna position, or the observing conditions.

Results from the Bonn correlator were treated in a similar way. All the scripts that set up the correlator were made available by Walter Alef. In these files the clock off–sets and rates for each experiment are stored. Here too we have to rely on the notes in the files for indications that fringes to a particular telescope were indeed found. The appropriate parts of the files were filtered out and stored in the same way as the GPS data.

Finally, when I collected the correlator data I tried to distinguish between several antennas at a site, and observing frequency. For two antennas different offsets may be expected for two dishes, depending on the details of cabling. Similarly, different receivers may yield different results. Unfortunately it will turn out that there is not enough data (yet) to say anything about the receiver dependence.

Results

The VLBA correlator

The most straightforward comparison is to plot fits to the GPS data and the fringe search output obtained at the VLBA correlator. In all clock searches the VLBA telescopes are used as a reference. But the results are not stored relative to a certain VLBA antenna. The results of GPS monitoring at VLBA sites are stored in the correlator database. For each telescope the clock delay and rate are predicted, and inserted in the correlator table before clock searching. From experience we know that typically the VLBA antennas come out within 200 ns. These residuals seems to have a station based offset component of as much as 100ns in some cases, which is not taken out at the VLBA yet. The rms spread is approximately 50 ns (Walker, VLBA test memo #60). This system has been reliably operational since mid 1993, only results after April 1 1993 are used in the analysis. So, any of the VLBA antennas can be used as a reference to predict the “average VLBA GPS time” to a comfortable accuracy (usually either the Hancock or Saint Croix antenna are used because of their eastern location). In principle there can be an ”offset” left; as all the VLBA antennas are almost identical there may be an equal extra delay at all sites between “VLBA time” and the real thing.

This procedure allows a direct comparison of the predicted delay versus measurements, assuming that the dominant effect in a specific experiment comes from the clock. This may

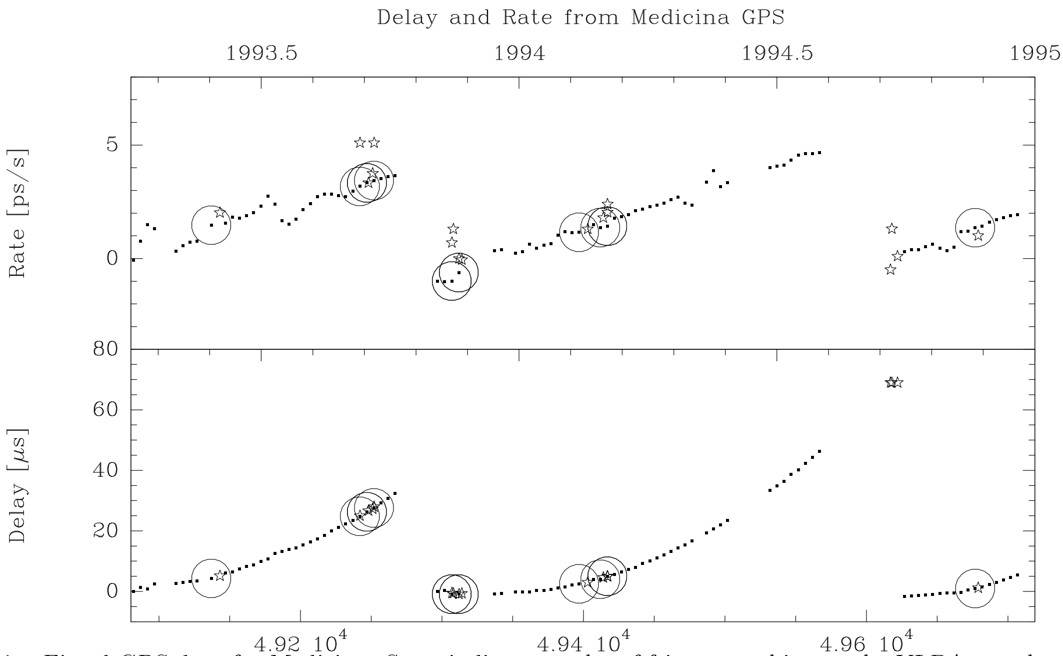

Fig. 1a. Fitted GPS data for Medicina. Stars indicate results of fringe searching at the VLBA correlator. The large circles denote the closest value of the fitted GPS data. The circled value was used to derive the residual and rms in Table 2.

not hold, for instance, at 327 MHz, where the atmospheric delay may be as large as 1 μs, thus reducing the accuracy with which we can compare the correlator results to the GPS predictions. More severe is the impact of such effects on the rate. Inaccurate telescope and source positions can easily dominate this comparison. Until recently the VLBA correlator model did not perform an interpolation of aberration and Earth orientation parameters. The residual could be clearly seen when a project crossed midnight; rates would usually jump on 0h UT sometimes by by as much 1.5 ps/s. Thus, depending when a fringe search was done, discrepant rates of this order of magnitude can be expected.

Results for Medicina, Onsala (65 feet) and Metsahovi are shown in Fig. $1a-c$.

These fits show clearly the predictive power of the GPS clocks for measuring the delay. The case for the rate is less clear; this is mostly due to imperfections in the correlator model as described above. Furthermore, these measurements come mostly from global experiments at 22 GHz, where small station and source offsets can produce noticeable rates.

I summarize the results of these measurements in Table 2.

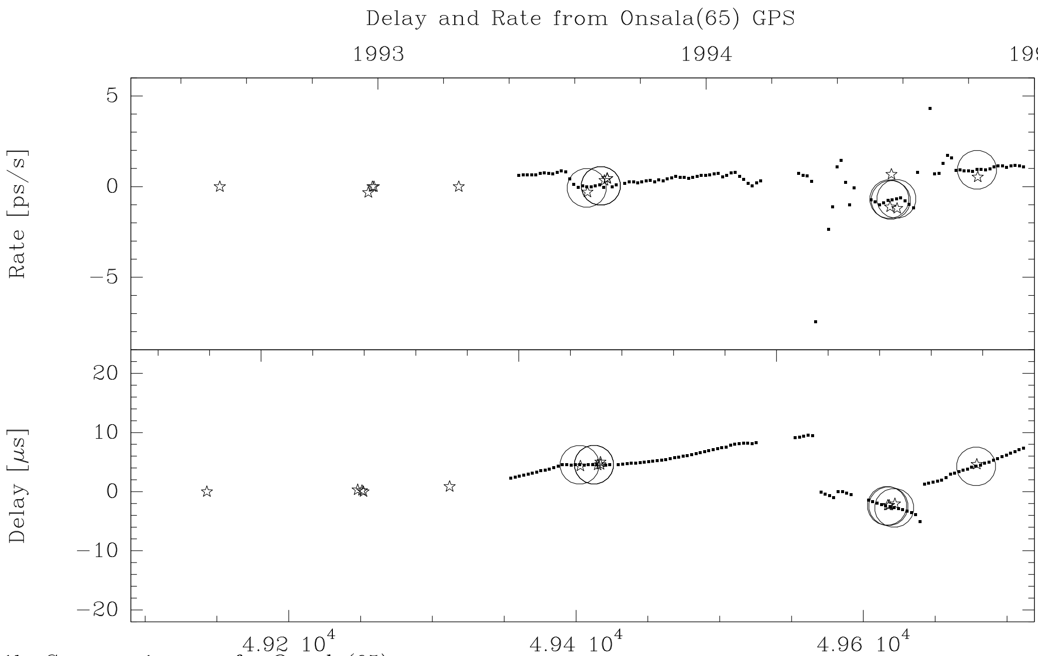

Fig. 1b. Same as 1a, now for Onsala(65).

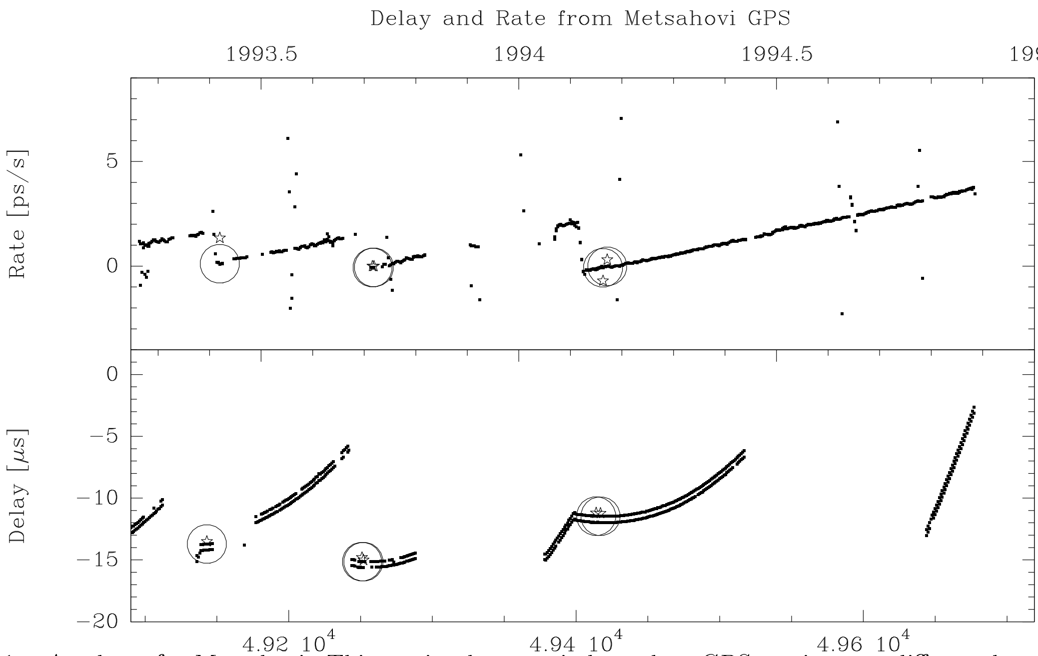

Fig. 1c. As above for Metsahovi. This station has two independent GPS receivers at different location, resulting in two fits with a delay offset.

Table 2. GPS measurements compared to correlator results

Station	Correlator and Reference GPS		N	Average residual GPS–maser			
				Delay		Rate	
				μs	rms	ps/s	rms
Medicina	Socorro	VLBA	14	–0.13	0.20	–0.82	0.78
Metsahovi1	Socorro	VLBA	5	–0.24	0.07	–0.21	0.67
Onsala (65)	Socorro	VLBA	8	–0.20	0.29	–0.15	0.67
Jodrell (MkII)	Bonn	VLBA	1	16.98	—	0.94	—
Medicina	Bonn	VLBA	8	0.02	0.20	–0.30	0.73
Onsala (65)	Bonn	VLBA	3	–0.03	0.19	–0.09	0.30
Onsala (85)	Bonn	VLBA	1	2.90	—	0.08	—
Metsahovi	Bonn	Medicina	3	–0.06	0.28	2.42	0.18
Onsala (85)	Bonn	Medicina	10	2.68	0.22	4.23	1.78
Onsala (65)	Bonn	Medicina	6	–0.11	0.26	4.47	1.91

Results with the Bonn correlator

The Bonn files reference their rates and delays to one of the telescopes in the array, for astronomical observing usually Effelsberg. We can only test the predictive power of the GPS clocks when we have GPS values for two telescopes in the network. My first approach was to use the VLBA antennas. For these the same clock description as is used in the VLBA correlator was made available by Jon Romney. Going through the Bonn correlator file, all projects which included VLBA antennas were selected after April 1 1993. The VLBA prediction was subtracted from the clock difference between the antenna of interest and the VLBA antenna. This yields a time as measured by the Bonn correlator, to the extend that we can trust the VLBA clocks. Again careful inspection of the correlator files was needed to be certain valid entries were used. Still, the approach yields satisfactory results as indicated in an example, Fig. 2. The results of this procedure are also given in Table 2.

The number of comparisons we can make with the procedure described above is limited; not that many VLBA antennas participate in projects that get correlated in Bonn. So the same technique was used, but now referencing to Medicina. This antenna participates in a great number of projects and had reasonably complete GPS data over the time of interest. The goal is to find some results for the antennas that have very few measurements from the previous attempts. A good example is the Onsala 85 feet (Fig. 3). Clearly there is an offset between the time estimated from the correlator and the time of the GPS. This may be due to the fact that the hydrogen maser at Onsala is located at the 65 feet, and an extra delay results from the extra cabling, although the offset seems to be large. A summary of

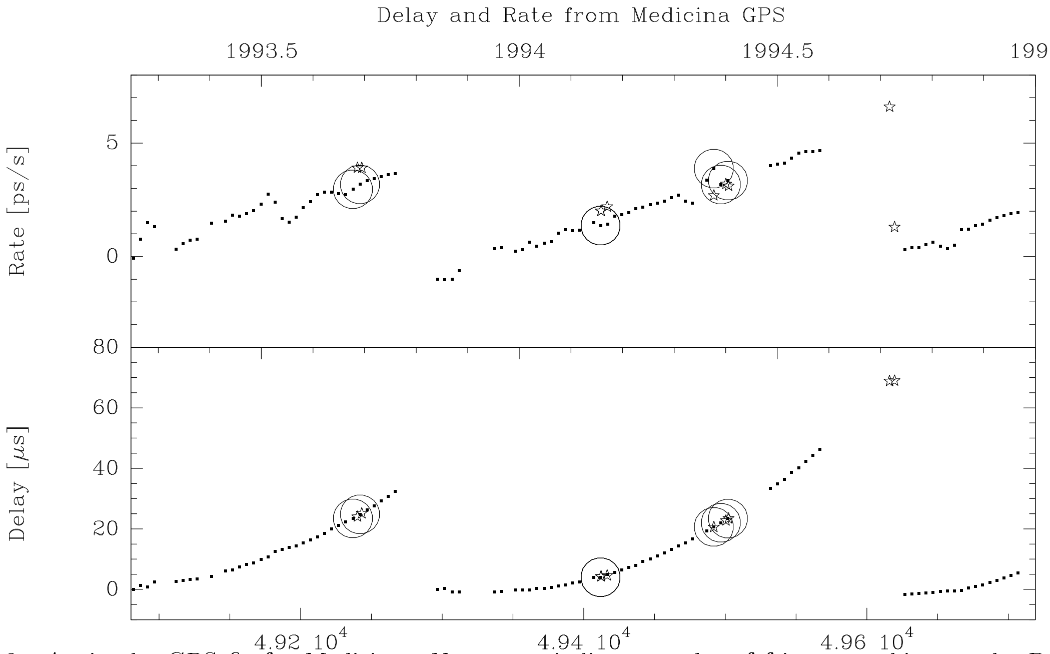

Fig. 2. Again the GPS fit for Medicina. Now stars indicate results of fringe searching at the Bonn correlator, referenced to the VLBA GPS, by means of the participating VLBA antennas.

results obtained with respect to the Medicina GPS through the Bonn correlator is given in the last part of Table 2.

Conclusions

The results of Table 2 indicate that GPS sources can yield good enough a–priori clock values to omit the fringe searching step for most astronomical purposes. In some cases there are significant offsets between the predicted and found delay. But the spread in the residuals indicates that if we calibrate these offsets a predicted delay can be obtained with an rms of 200 nanoseconds with current systems. If we streamline our system there should be no reason why we cannot get to 100 or 50 ns. The 200 ns corresponds to a few degrees of phase in a typical continuum channel of 250 kHz, or a loss of less than 0.5%.

With the current data it was possible to see the differences between different dishes at a particular site. In principle the extra path lengths should be calibrated by comparing more measurements than we have available now. Ideally we should also have receiver dependent GPS calibration factors. The amount of data currently available is too limited for that. To ensure future calibration of these factors, careful collection of GPS data is needed, as well as a mechanism at the correlators to store the results of the clock searches more accurately.

The accuracy with which we can check the prediction for the clock rates from the GPS data is limited. It is clear that the GPS can determine the rates much more accurately

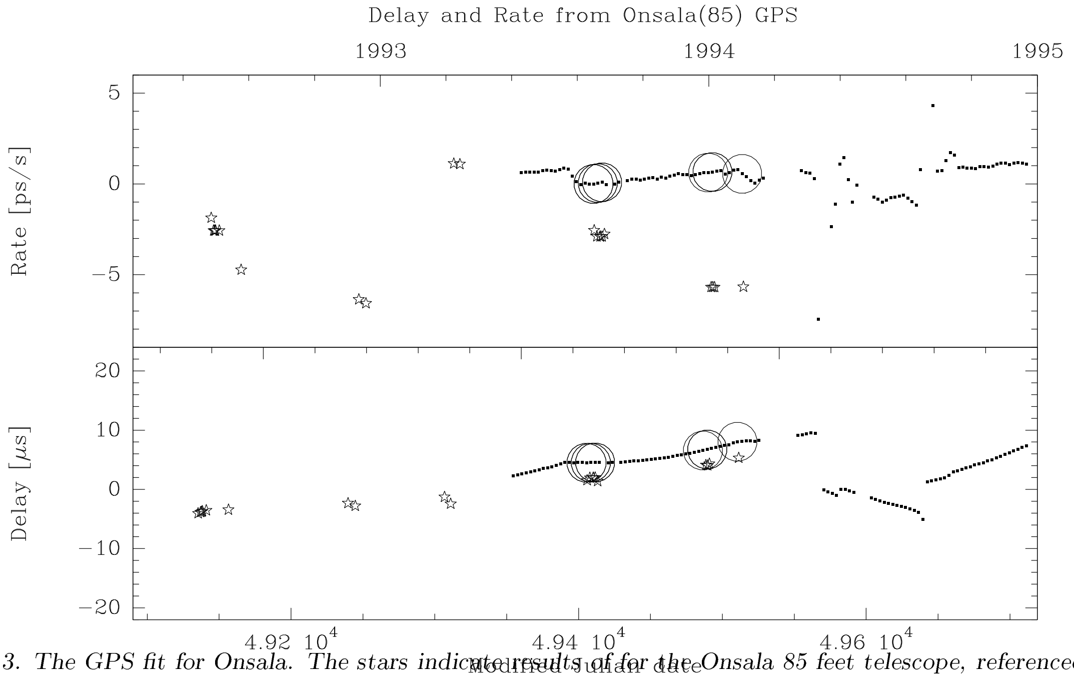

Fig. 3. The GPS fit for Onsala. The stars indicate results of for the Onsala 85 feet telescope, referenced to the Medicina GPS.

than the correlators can check them at the moment. However, it is also clear from some of the figures that rates larger than 0.5 ps/s are noticeable at the correlators, and that such rates do occur around the network. Determination of the rates is therefore already relevant and may become more important if the accuracy of correlator models, especially the atmospheric part, increases. At 22 GHz 0.5 ps/s corresponds to 3 s averaging without more than 0.8% losses.

In Appendix A a proposal is formulated to record the necessary information in a consistent way around the network. Another possible approach would have been to record clock values in the log files, as happens at several stations already. These values are very useful and everybody is encouraged to (continue to) write them in the logs as comments. However, they cannot provide us with the same accuracy. One problems is that poor readouts cannot be recognized. And, in particular, there is no hope to get the rates, as this requires monitoring over a large number of days. For the same reason it *not* a good idea to reset the maser clock regularly; a well determined delay and rate are better than values close to zero. For the same reason it is suggested not to do maintenance on the maser within $\approx$ 4 weeks of a session.

Appendix A
GPS proposal 12Jan95, with updates (13Apr95, 26Apr95)

All EVN observatories now have GPS receivers so we need an agreement about a format for distributing this info. This will allow people who do not yet have a setup to standardize on one interface for Mk3 and Mk4 systems. This is modeled closely on the processing of VLBA GPS monitor data by Jon Romney.

What we must measure

- Measure the time offset between GPS and formatter 1pps and average to approximately 1000 seconds. This is usually long enough to average out any local biases in the pps measurement.
- Filter out poor readings. GPS observations flagged at the receiver; offset > 0.5 seconds.
- Average up to one UT day. On shorter time scales the maser stability should be adequate and the GPS value is poor due to the artificial dither in the signal. Note:

  The average time for which the offset is measured (in MJD)

  The average offset

  The rms error on the offset
- Filter out poor daily averages (>200ns r.m.s.)

Procedure

Clock offsets should be monitored continuously all year. Data should be examined at least monthly (by hand) and the file edited to insert comments about known local changes that could affect the GPS–maser offset. This is the responsibility of VLBI friends. Long term continuity of behavior is important. As a minimum the offset should be monitored from at least 1 week before a session, throughout the session, to at least until 1 day after the session.

The Friends are also responsible for sending the updated data file monthly to the Bologna VAX `astbo1.bo.cnr.it`, ftp into the subdirectory `[EVN.GPS.MMMYY]`, where Huib van Langevelde will look after archiving the data when it is older than 2 years.

Huib van Langevelde emphasizes that he is interested in getting any GPS clock offset data as soon as possible, rather than waiting for a standard file format to be implemented at your observatory. He is also interested in the unaveraged (1000 second) data. If your data does not follow the proposed format outlined below then mail a full description of it to Huib van Langevelde (hvanlang@aoc.nrao.edu) before depositing it.

Proposed File format

The data file will be identified by a name GPS.<obs_code> where <obs_code> is the standard 2-letter code for the observatory. This convention is the same as is used for schedules and log files at present.

The file format will be in ASCII and have three types of lines.

1. A clock line
   - MJD: modified Julian day for the average time for this UT day's observation. This should have at least 3 decimal places.
   - space
   - clock: offset GPS–formatter, in microseconds with at least 2 decimal places.
   - space
   - rms: r.m.s. on the clock offset, also in microseconds with at least 2 significant digits.
   - space
   - GPS receiver identification: A name which identifies the GPS source. Some observatories have several GPS timing receivers, so each should have a unique name. It is suggested that the name should have the format GPS<xx><n> where <xx> is the observatory's 2 letter code and <n> is the number of the GPS receiver. Do not change this name unless the observing setup changes. If this does occur a 'separation line' (see below) should be given.
   - comments: anything after the 4th column is a comment on this day's observation.

   As an example:

```
49730.517 12.571 0.043 GPSWB1 some problems with GPS at about 0930UT
```

2. Pure comment line. This should start with a "#" character and contain info about local changes, or excuses why data is missing! As an example:

```
# Our GPS system was dead today because the antenna fell off the roof
```

3. Separation line. This should start with a "&" character and mark separate periods where discontinuous behaviour is expected. The software that processes the data into a form that describes the long term behaviour can detect breaks, but comments about suspected changes can be very useful. Examples of changes in the maser or GPS system are:
   - maser offset compensation
   - maser drift compensation
   - new GPS position
   - new cabling setup

   Anything after the ampersand is an explanation. As an example:

```
& demagnetised the maser today.  This should reduce clock rate.
```

Appendix B; Remaining plots

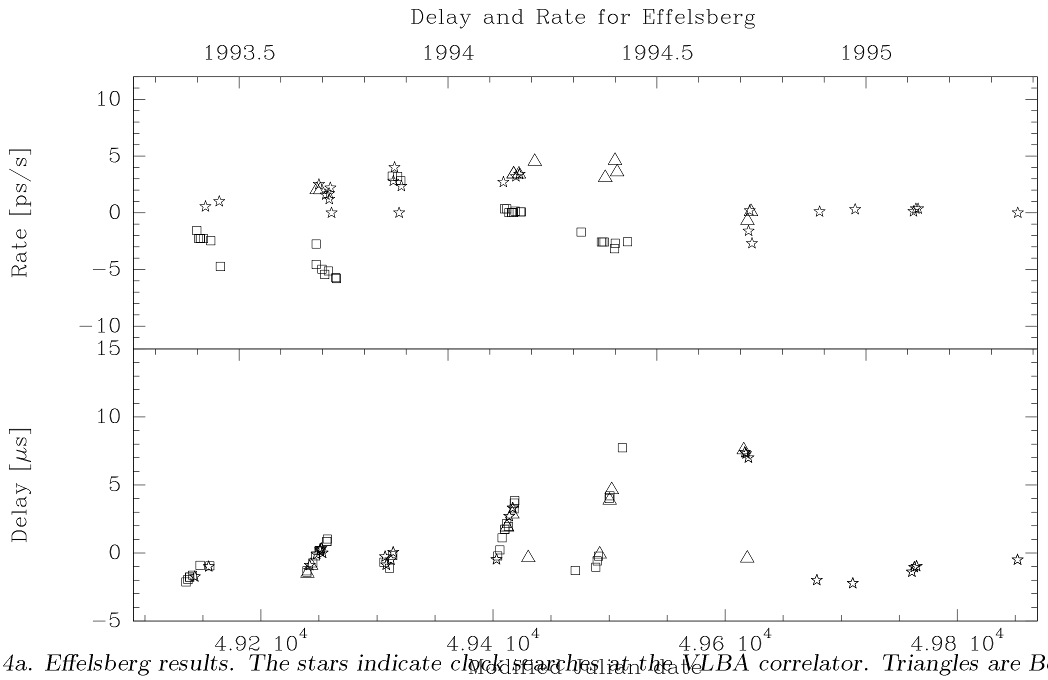

Fig. 4a. Effelsberg results. The stars indicate clock searches at the VLBA correlator. Triangles are Bonn results were the VLBA GPS was referred to, squares are relative to the Medicina GPS.

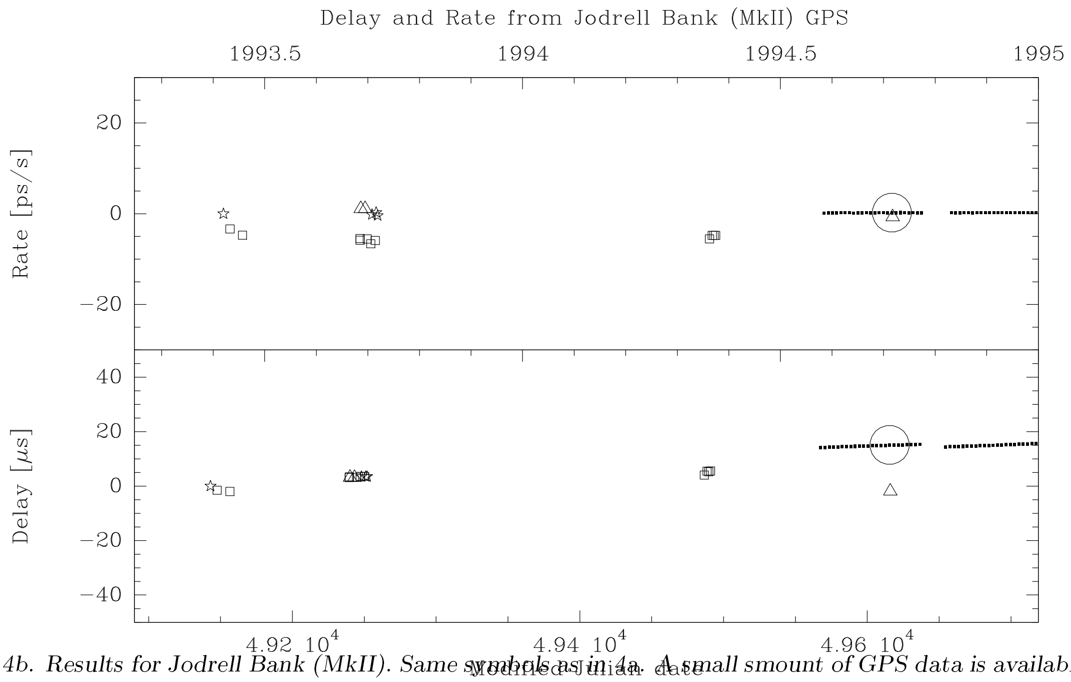

Fig. 4b. Results for Jodrell Bank (MkII). Same symbols as in 4a. A small smount of GPS data is available for this station.

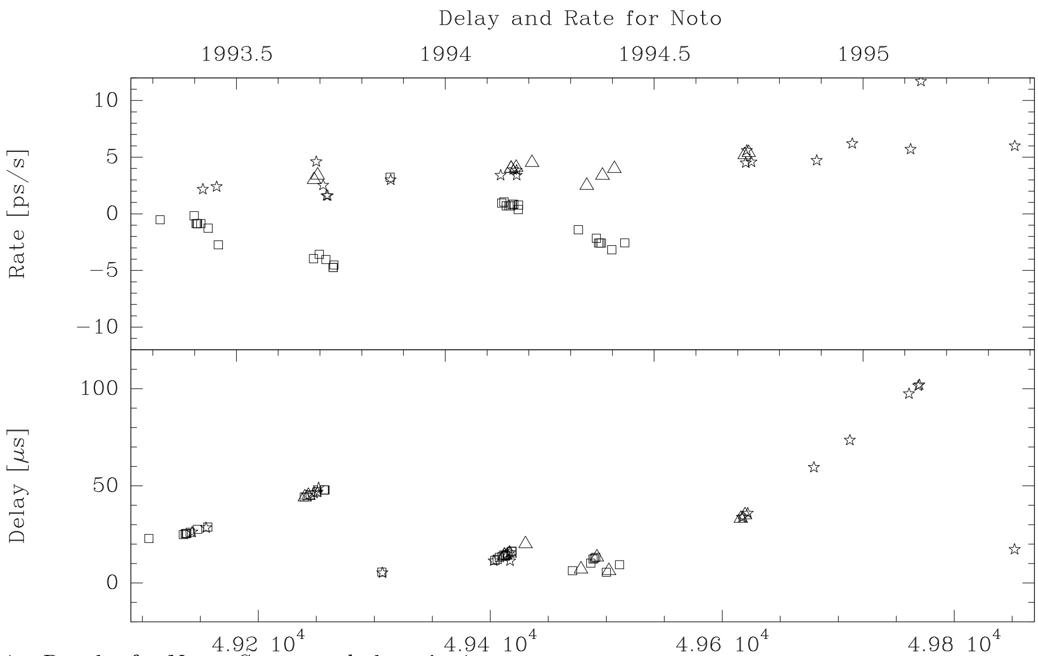

Fig. 4c. Results for Noto. Same symbols as in 4a.

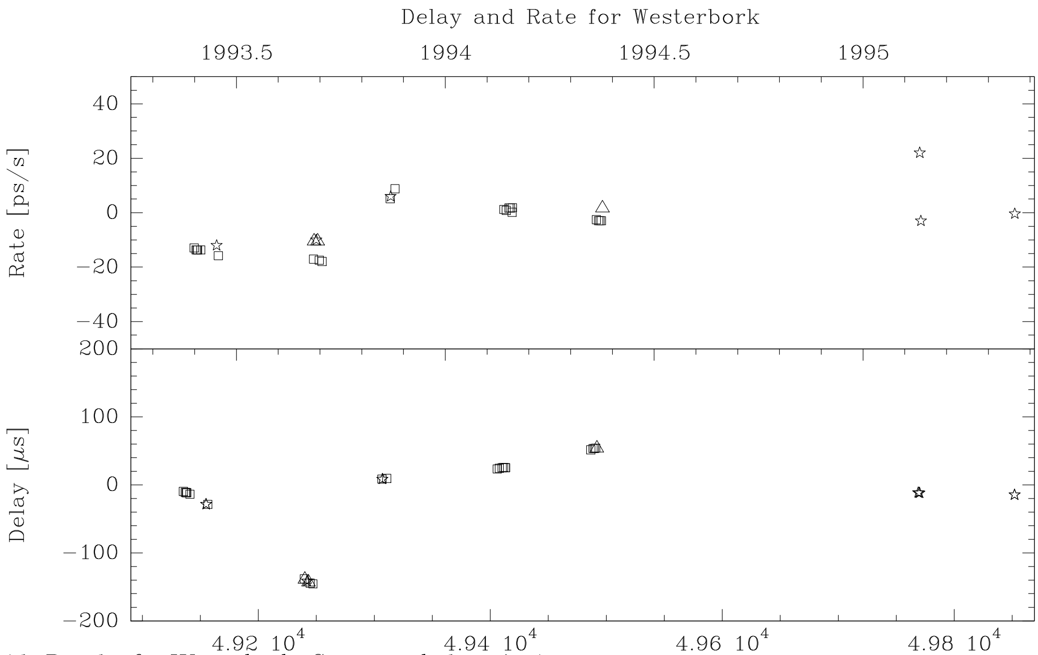

Fig. 4d. Results for Westerbork. Same symbols as in 4a.