The Demise of Selective Availability and Implications for the International GPS Service

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Physics and Chemistry of the Earth

Manuscript-No. ???

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Received ??? – Accepted ???

Abstract. Early on May 2, 2000, selective availability (SA) – the intentional dithering of clocks on GPS satellites – was terminated. The amplitude of variations in transmitter clocks, formerly tens of meters, was reduced by orders of magnitude. These clocks are now much more predictable, with the possibility that the International GPS Service (IGS) can produce, in addition to real-time orbits, real-time *clocks* that are significantly higher quality than those in the broadcast ephemeris. Furthermore, the meaning of *high* in "high rate ground network" to support LEO missions needs to be re-examined.

1 Introduction

Selective Availability – the intentional dithering of clocks on GPS satellites – meant that, until recently, these clocks deviated from a linear (in time) function by tens of meters over timescales of minutes. One consequence was that precise real-time estimates of these clocks, based on prediction, required few-sec data latency. A second consequence was that post-processing of kinematic GPS data – or indeed any GPS data with information content on timescales of seconds to minutes – required knowledge of transmitter clocks at rates substantially more frequent than once every 30 s, the nominal IGS rate. (Equivalently, for processing strategies based on doubly differenced data types, frequent data from a reference site would be required.)

As of May 2, 2000, the situation has changed dramatically. Shown in Figure 1 are clock estimates every 30 s from svn46 (prn11) for a 30-hr period beginning May 1, 2000 at 21:00. Compared to the large and rapid fluctuations during the first few hours shown, after about 04:00 on May 2, there is no visible variation. (In fact, the rms scatter is about 7 cm during the flat portion.) This transition is visible for all transmitters.

In this position paper we first provide a cursory look at GPS transmitter clock variability in the post-SA era to see how well one can interpolate and extrapolate as a function of frequency, extrapolation time, and transmitter ID. (Kouba has made a preliminary assessment of these; see IGSMail 2824.)

Second, we examine the quality of IGS orbit predictions as a function of prediction time and network distribution.

Network-related questions we seek to answer include:

- At what rate should data be provided from the IGS sub-network to support precise post processing of kinematic GPS data and data from low-Earth-orbiting satellites carrying GPS receivers?
- How accurate might an IGS real-time orbit and clock be as a function of latency from this sub-network?

2 Interpolation of Clocks

Consider precise sequential estimates of a GPS transmitter clock x_i at times t_i with δ spacing (that is, $t_{i+1}-t_i=\delta$). One practical way to assess clock smoothness is to compare the value of x_i with one based on cubic interpolation of four neighboring points with spacing $2n\delta$, for $n \geq 1$:

$$\Delta_i = \frac{9(x_{i+n}+x_{i-n})-(x_{i+3n}+x_{i-3n})}{16} - x_i \, . \qquad (1)$$

Shown in Table 1 are the rms values of Δ_i as a function of transmitter and spacing, based on JPL's "high-rate" ($\delta = 30$ s) estimates of x_i over a two-week period beginning May 7, 2000. The columns correspond to $n = 1, 2, 3, 4$ and spacing $2n\delta = n$ min. A summary is shown in Figure 2, which has the median value of each column from Table 1 plotted as a function of spacing. (Note that the plotted values have been reduced by $\sqrt{2}$

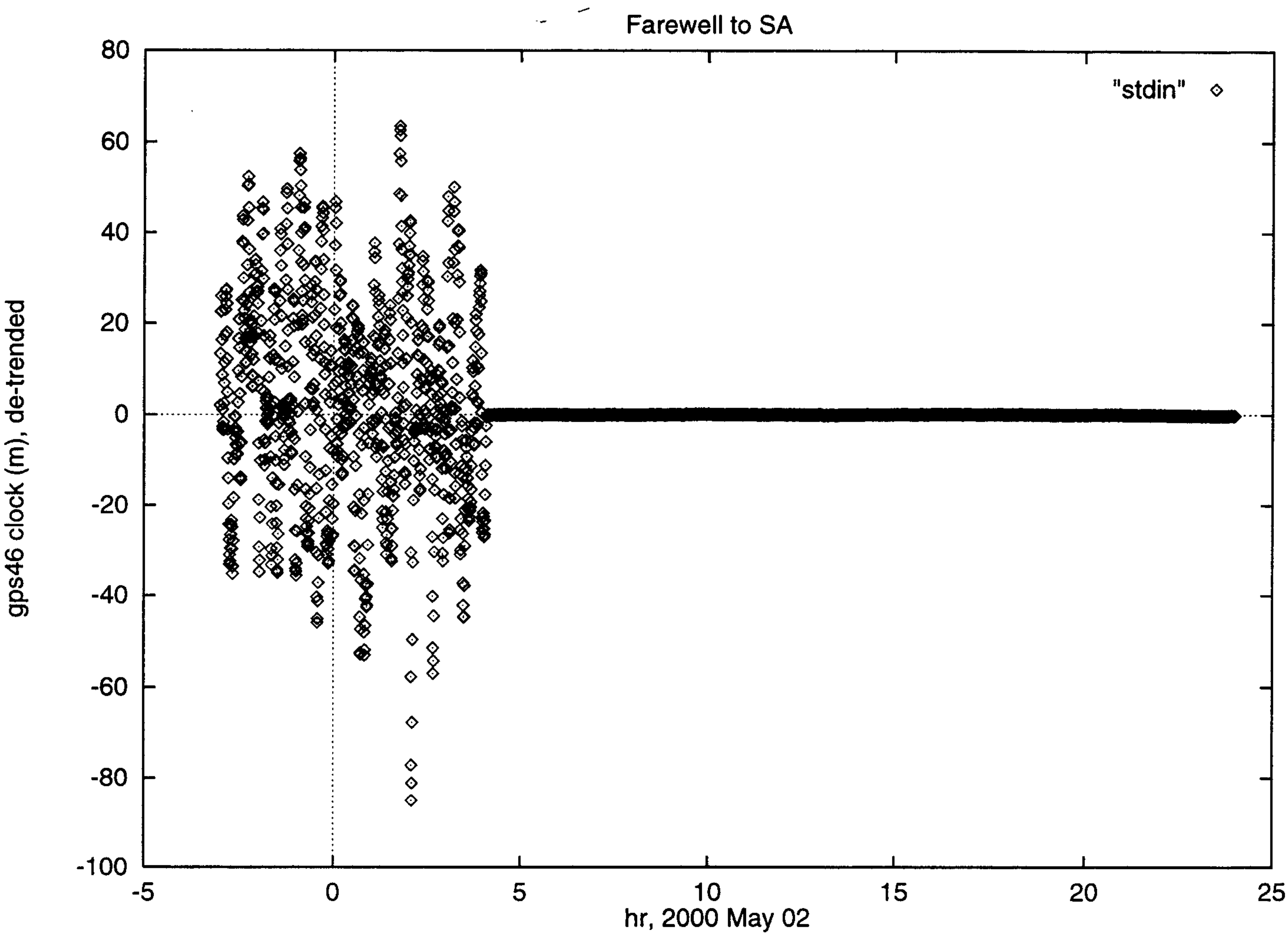

Fig. 1. Clock estimates every 30 s for svn46. Early on May 2, selective availability was terminated.

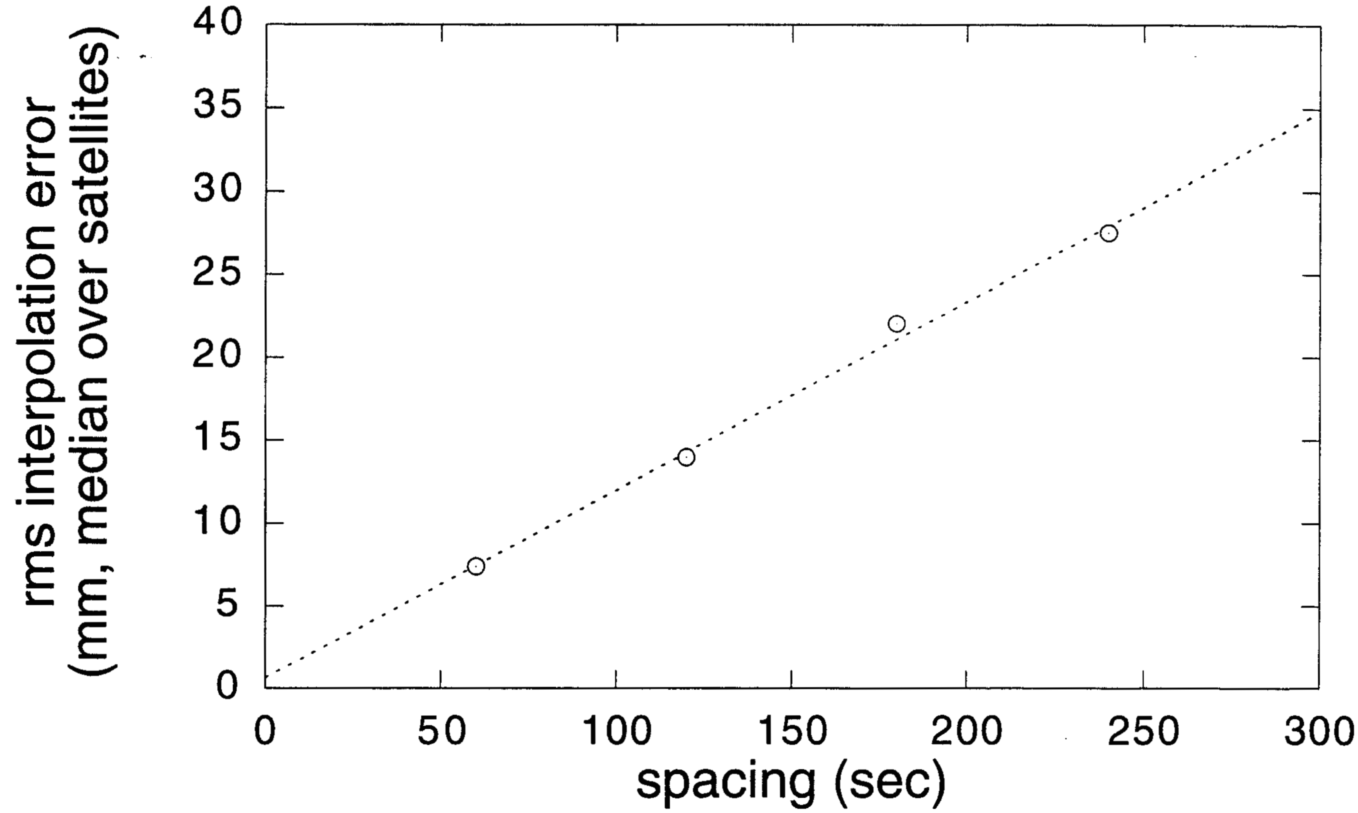

Fig. 2. Cubic interpolation error (rms, median over satellites, divided by $\sqrt{2}$) as a function of spacing.

Table 1. Interpolation error for value (mm, rms) and rate (mm/s) of transmitter clocks, as function of transmitter and spacing.

	value (mm)				rate (mm/s)			
	1 min	2	3	4	1 min	2	3	4
prn								
01	9	20	32	44	0.23	0.55	0.71	0.81
02	9	20	31	43	0.24	0.55	0.71	0.80
03	13	26	38	49	0.33	0.75	0.90	0.96
04	10	14	17	19	0.24	0.41	0.40	0.40
05	10	22	35	47	0.26	0.61	0.78	0.88
06	9	19	30	42	0.22	0.52	0.67	0.77
07	8	11	13	15	0.19	0.34	0.32	0.32
08	10	15	18	20	0.25	0.44	0.43	0.42
09	11	24	35	44	0.29	0.68	0.82	0.87
10	14	28	40	50	0.35	0.79	0.94	0.99
11	10	18	24	29	0.33	0.58	0.63	0.60
13	11	18	23	29	0.26	0.52	0.56	0.58
16	13	18	21	24	0.30	0.53	0.52	0.52
17	9	21	35	50	0.23	0.57	0.77	0.90
19	12	27	44	61	0.30	0.75	0.98	1.11
21	21	42	58	71	0.54	1.20	1.39	1.43
22	19	58	57	17	0.57	1.85	1.80	0.47
23	9	18	28	37	0.22	0.50	0.63	0.70
24	10	13	16	18	0.23	0.40	0.39	0.39
25	17	33	45	55	0.44	0.95	1.08	1.11
26	8	11	13	14	0.19	0.32	0.31	0.30
27	8	17	27	39	0.20	0.46	0.60	0.70
29	13	15	17	20	0.29	0.45	0.41	0.42
30	13	23	31	37	0.33	0.68	0.75	0.76
31	15	32	49	63	0.38	0.91	1.15	1.25

to account for the fact that the interpolation error is maximum midway between two interpolants.)

Although Table 1 indicates significant variability among transmitters, for a "typical" transmitter we show in Figure 2 the median (over satellites) values. This figure suggest that the typical rms interpolation error from the current IGS combined clock at 300-s spacing is about 3.5 cm. At 30-s spacing, such an error is be reduced to about 4 mm. (In the SA era, this was about 8 cm or 20 times larger.) An increase in the rate from measurements every 30 s to measurements every 10 s would further reduce the median interpolation error to less than 2 mm.

To support occultation measurements from low-Earth-orbiting satellites carrying GPS receivers, the quantity of interest is the transmitter *rate*. Knowledge of these rates to the level of 0.1 mm/s is the typical requirement to allow interpretation of such measurements.

We have numerically differentiated the 30-s clock estimates and performed a similar analysis to determine the error in interpolation for the transmitter rates; these are shown as the rightmost four columns in Table 1; median (over satellites) values are plotted in Figure 3.

Figures 2 and 3 suggest that operating the IGS network at 0.1 Hz would be sufficient to support both precise kinematic post-processing of arbitrary GPS data, as well as the analysis of occultation data from LEOs.

Unfortunately, based as it is on 30-s data, this analysis can only suggest the consequences of clock variability on shorter time scales. Since several months of 1-s data have been accumulated already at a number of IGS sites, it would make sense to use these to estimate transmitter clocks at 1 Hz. Such estimates would provide the basis for more definitive statements about what is really required to support precise kinematic post processing and occultation measurements.

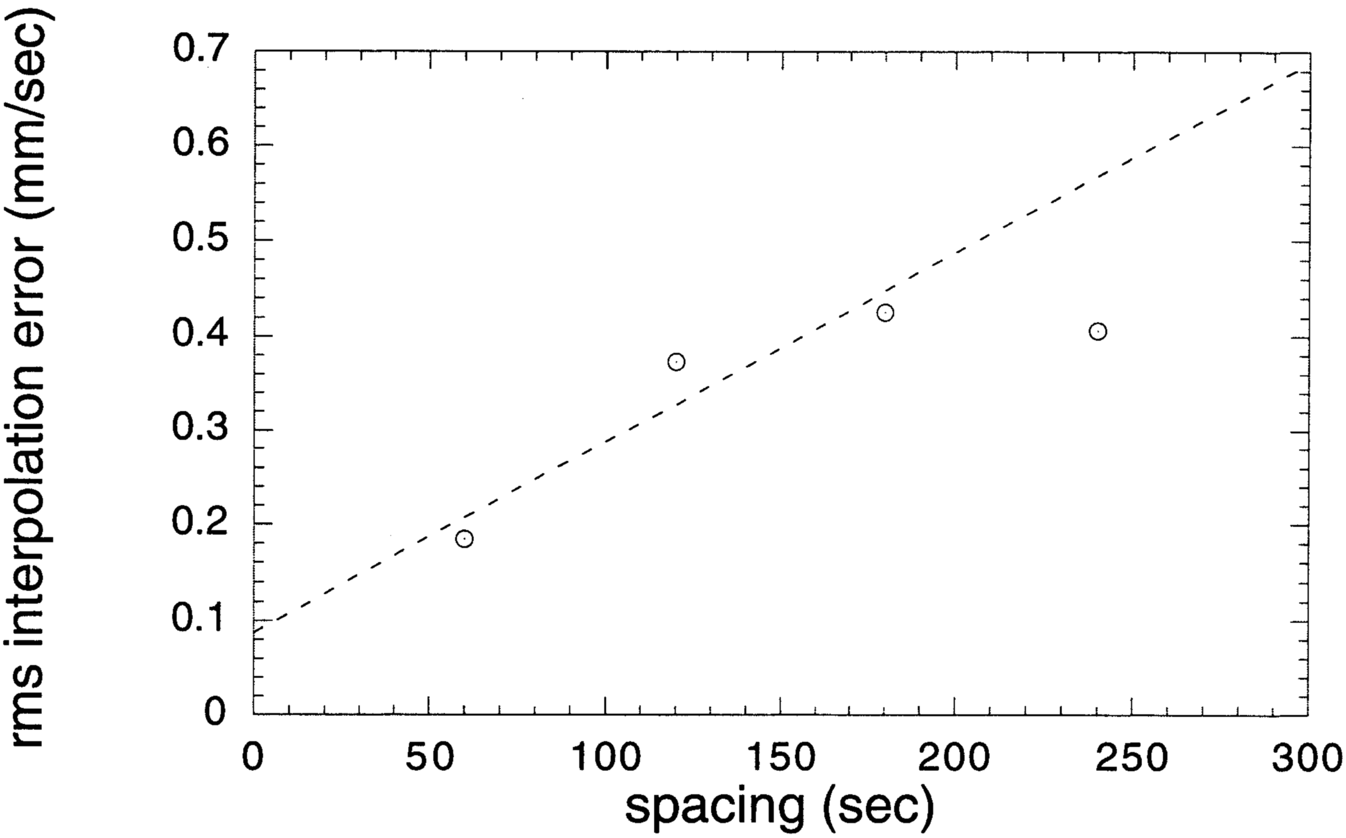

Fig. 3. Cubic interpolation error of clock rate (rms, median over satellites, divided by $\sqrt{2}$) as a function of spacing.

3 Extrapolation of Clocks

The previous discussion showed that, in the post-SA era, measurements every 10 s from a ground network, which in turn produce estimates of transmitter clocks at the same rate, are probably sufficiently frequent to support precision post processing of both kinematic GPS data and occultation data from LEOs.

For potential real-time applications, the question is one of extrapolation rather than interpolation. The IGS has produced for some time a real-time orbit, based on prediction, that is significantly more accurate than that in the broadcast ephemeris. Until now, however, SA has meant that transmitter clocks were inherently unpredictable. How has the situation changed?

Suppose that, based on measurements at times $t < 0$ we have estimates x_i of a transmitter clock corresponding to times $t_i = i\delta$ for $-N \leq i \leq -1$. Using these and a linear model, we determine m and b in the usual way by minimizing the mean square value of $mt_i + b - x_i$ over $-N \leq i \leq -1$.

Next, we use this model to predict values of the clock for $t \geq 0$, and compute the rms deviation over an interval of width $M\delta$ from what was estimated using data:

$$D = \sqrt{\frac{1}{M}\sum_{i=1}^{M}(mt_i + b - x_i)^2} \; . \tag{2}$$

Again, an interval $N\delta$ is used for determining the values of m and b, and an interval $M\delta$ is used for extrapolation[1]. It is reasonable that these intervals be similar. We show in Table 2 the values of D, assuming $N = M$, as a function of transmitter ID and extrapolation time. As in Table 1, we use JPL's high-rate clock estimates for two weeks beginning May 7, 2000.

The median (over satellites) extrapolation error is shown in Figure 4. For truly linear clocks with white noise, one would expect this curve to have a negative slope (see footnote). That it slopes upward is indicative of more complicated behavior. The figure thus gives a pessimistic view of clock prediction. By studying the temporal variations, one ought to be able to predict clocks significantly better than shown there.

Nevertheless, even with the simplified model, Figure 4 indicates that IGS could produce a real-time clock with an accuracy depending on the data latency and time for analysis. For example, with instantaneous analysis of hourly data, a real time clock with 50-cm accuracy could be realized.

[1] In the case where $N = M$ and the errors in the x_i are white, it can be shown that (2) is approximately equal to $\sqrt{(13/N)^2 + 1}\,\sigma$, where σ is the error in estimated values of x_i. The $13/N$ arises from the extrapolation, and the 1 from the fact that the extrapolation is compared to an estimate, not truth.

Table 2. Extrapolation error (cm, rms) as function of transmitter and extrapolation time.

prn	2 min	5 min	10 min	20 min	40 min	80 min	4 h	12 h
01	6	15	23	35	49	76	145	193
02	6	14	23	36	58	83	151	188
03	7	14	20	29	43	70	133	124
04	3	4	6	8	12	18	37	65
05	7	16	26	37	53	80	160	180
06	6	15	24	36	55	101	201	264
07	2	3	4	6	9	17	60	128
08	4	8	7	13	24	49	168	196
09	7	13	18	27	40	55	93	162
10	8	14	20	28	36	55	117	175
11	5	7	7	6	9	7	21	23
13	5	10	20	32	36	29	49	74
16	5	7	8	11	16	22	61	176
17	7	19	32	51	71	102	153	171
19	9	22	36	51	76	111	175	219
21	11	19	27	39	56	85	125	147
22	9	5	6	7	19	13	41	72
23	6	12	20	29	43	77	193	184
24	3	4	5	7	11	17	26	53
25	8	14	21	30	45	62	124	111
26	2	3	4	6	8	13	35	62
27	6	15	26	42	64	97	160	220
29	3	4	6	8	12	16	29	74
30	6	9	13	17	25	41	122	124
31	10	17	25	37	50	71	139	158

4 Orbit Predictions

A comprehensive quality check for the IGS Ultra Rapid Product is presented in a separate paper by T. Springer (this volume; see also Gendt, G, P Fang, J F Zumberge: *Moving IGS towards real-time*, IGS Analysis Center Workshop, 8-10 June 1999, La Jolla, CA, USA, in press). In this paper we will look into the shortening of the predictions only, and will discuss the relation between orbit quality and site distribution.

In principle there should be no need for a very short repetition of the orbit predictions (in intervals of minutes). Satellite orbits are in most cases rather good predictable, at least for several hours.

Each ultra rapid analysis starts with an orbital adjustment taking into account the last 24 hours of data (using a sliding window shifted by 12 hours). The resulting SP3-products (named GFU-ADJ, ADJ for adjusted) are generated with the same technology which is applied for the corresponding rapid product (named GFR). For the proper ultra rapid product (GFU) a long orbital arc is fitted through the GFU-ADJ and the IGS rapid orbit for the day before, and then predicted for the next 24 hours.

All tests presented here are based on the GFZ internal ultra rapid products. All quality statistics are computed using the differences to the IGS final SP3-products, the accuracy of which is 2-3 cm. The statistics are given for 100 days (2000/024 to 2000/127).

At first the quality of the GFZ-ADJ orbits will be assessed. As soon as they reach the quality of GFR, they will replace them. At the moment the quality of the GFU-ADJ has not yet reached the level of GFR, although identical technology is used (Table 3, Figure 5). The favorite explanation is the sparse distribution of hourly sites in Asia and in the southern hemisphere.

To investigate the dependence of the orbit accuracy from the length of the prediction interval quality statis-

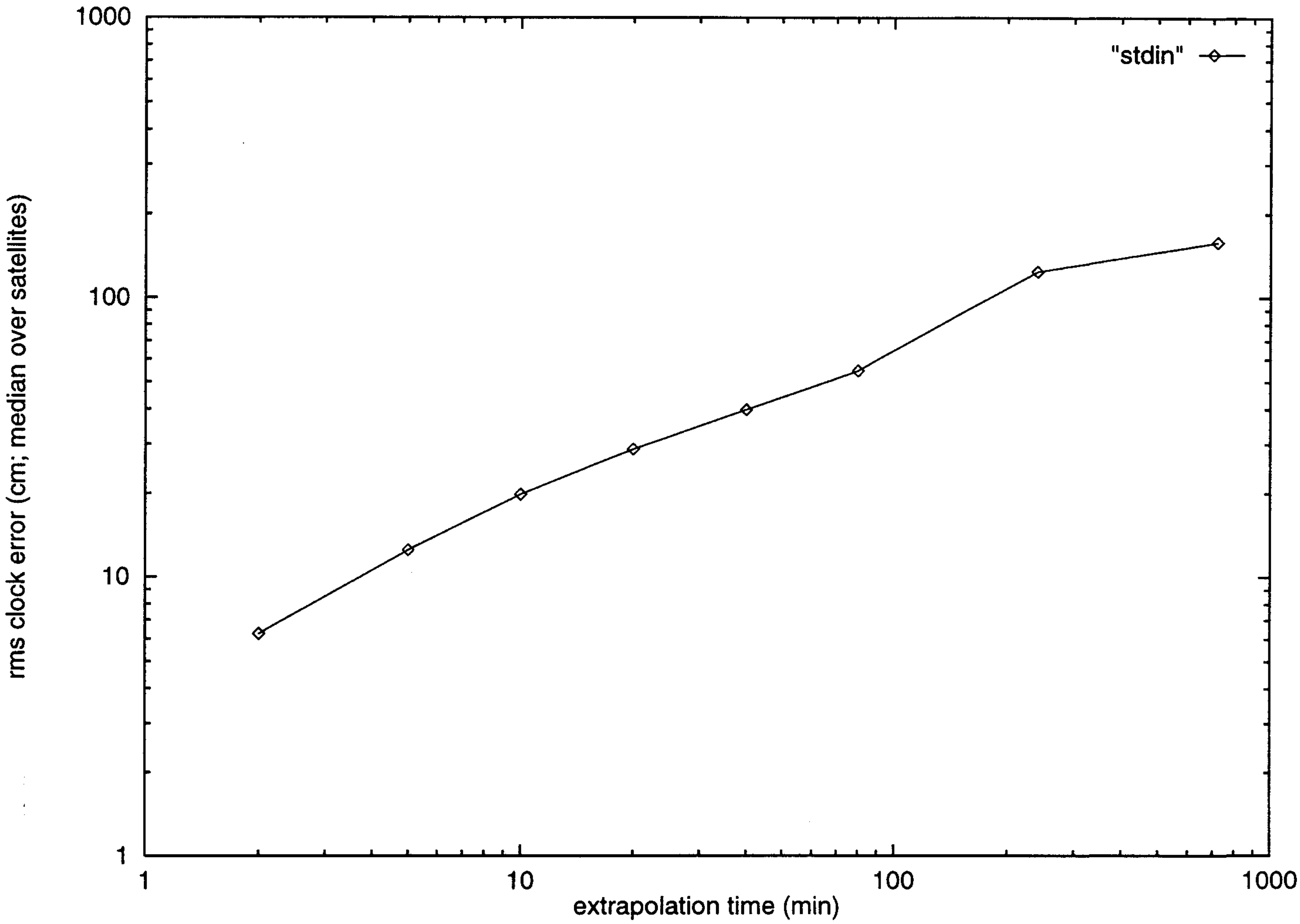

Fig. 4. Linear extrapolation error (rms, median over satellites).

Table 3. Quality of GFU-ADJ and GFR products for 24-hour intervals.

	orbit RMS (cm)	orbit median (cm)	clock RMS (ns)
GFU-ADJ	11.4	8.4	0.3-0.4
GFR	7.5	5.9	0.1-0.2

tics for the first 12 hours, separately for each 3-hour interval, are computed. In many cases we see a linear behavior in the improvement of median and rms, going from the 9-12 hour interval to the 0-3 hour interval (Figure 6). The linearity is more pronounced for the rms than for the median which implies that the shortening of the prediction interval is more relevant for the less predictable satellites. Corresponding statistics are given in Figure 7 and Table 4, as well as in Figure 8.

The basis of any good prediction is a good adjusted orbit. The optimal reachable prediction quality is the quality we have at the end of the adjusted orbit. Therefore in Table 4 and Figure 8 the statistics for the last 3-hour interval of GFU-ADJ and GFR are added. The systematic between all statistics from GFU-ADJ to prediction interval 9-12 are nicely seen. The percentage of satellites predictable better than 15 cm decreases from 77% to 49%, for better than 25 cm from 92% to 71% (Figure 8). A reasonable shortening of the prediction interval could be 6 hours, which will improve the results by 10% (compared to the prediction until 12 hours), and the number of outliers (orbits worse than 30 cm) reduces from 23% to 14%. A further reduction of the prediction interval will not help much to reduce the number of outliers. However, any shortening of the prediction interval should be discussed within the IGS in connection with the impact which a better network will bring and with the demands from the user community.

Figure 8 nicely demonstrates that in the moment the greatest potential for improvements is to reach the quality of GFR also for the GFU-ADJ orbits. As already mentioned before this depends on the improvement in the global hourly network.

To get for the real-time application a precise and reliable orbit a combination of high quality prediction over several hours should be combined with a near real-time integrity monitoring of the predicted orbits. The monitoring produces accuracy codes for the orbits. It is also possible to generate in near real-time satellite clocks which are compatible to the predicted orbits and may be used for precise point positioning.

Table 4. Quality statistics for different prediction intervals and for the last 3 hours of the data interval in the adjusted orbits.

	hours	RMS (cm)	median (cm)
GFU-Predi	9-12	27.4	16.9
GFU-Predi	6-9	24.3	13.8
GFU-Predi	3-6	21.5	12.4
GFU-Predi	0-3	18.6	10.8
GFU-ADJ	last 3 h	15.3	9.3
GFR	last 3 h	8.9	5.8

5 Conclusions and Recommendations

A tentative conclusion of this work is that a ground network with measurements every 10 s is sufficient to support precise post processing of kinematic and occultation GPS data. It is recommended that existing 1-Hz data should be used to verify and/or refine this conclusion. Before making a switch from 1 Hz to 0.1 Hz in its high-rate ground network, the IGS should consider the impact of such a switch on other customers (for example, those interested in rapid ionospheric variations).

(Although not related to the IGS network *per se*, we believe that the temporal variations of GPS transmitter clocks should be studied in sufficient detail – presumably with existing 1-Hz data as well – to allow a more optimal clock prediction scheme to be developed than the preliminary one presented here.)

To better support the generation of Ultra Rapid products, it is recommended that station operators move to hourly downloading and delivery of RINEX data, wherever practical, and especially for sites outside of Europe and North America.

Additionally, it is recommended that automatic procedures be developed and implemented so that a failure at a single Data Center will not disrupt the timely flow of hourly data.

(Another finding not specifically related to the IGS network is that IGS ACs should assess the feasibility of reducing the cycle for the IGS Ultra Rapid process from 12 hr to 6 hr, and thus reduce the orbit error due to extrapolation.)

Acknowledgements. A portion of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

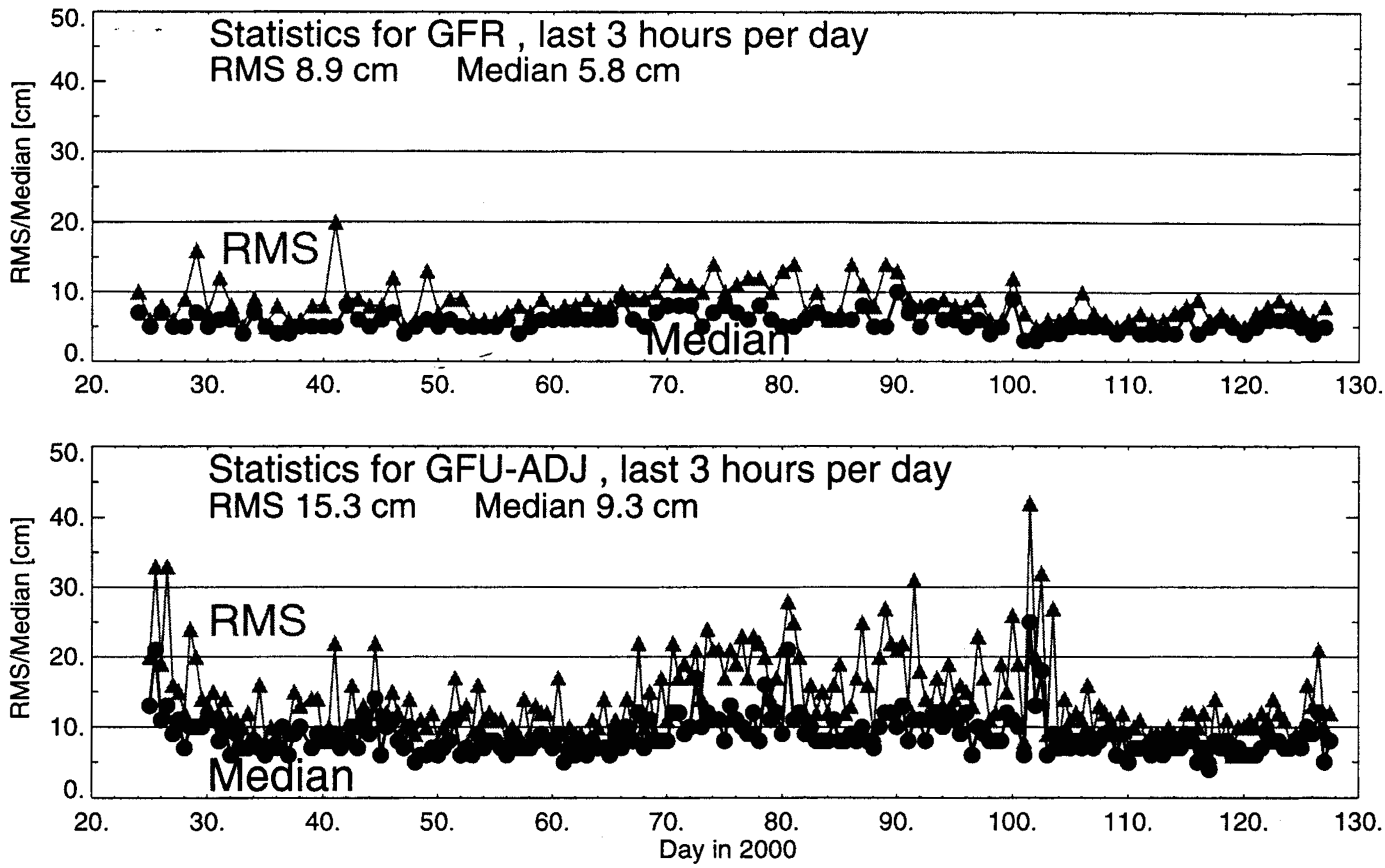

Fig. 5. The orbit quality of the last 3 hours is given for GFR and GFU-ADJ.

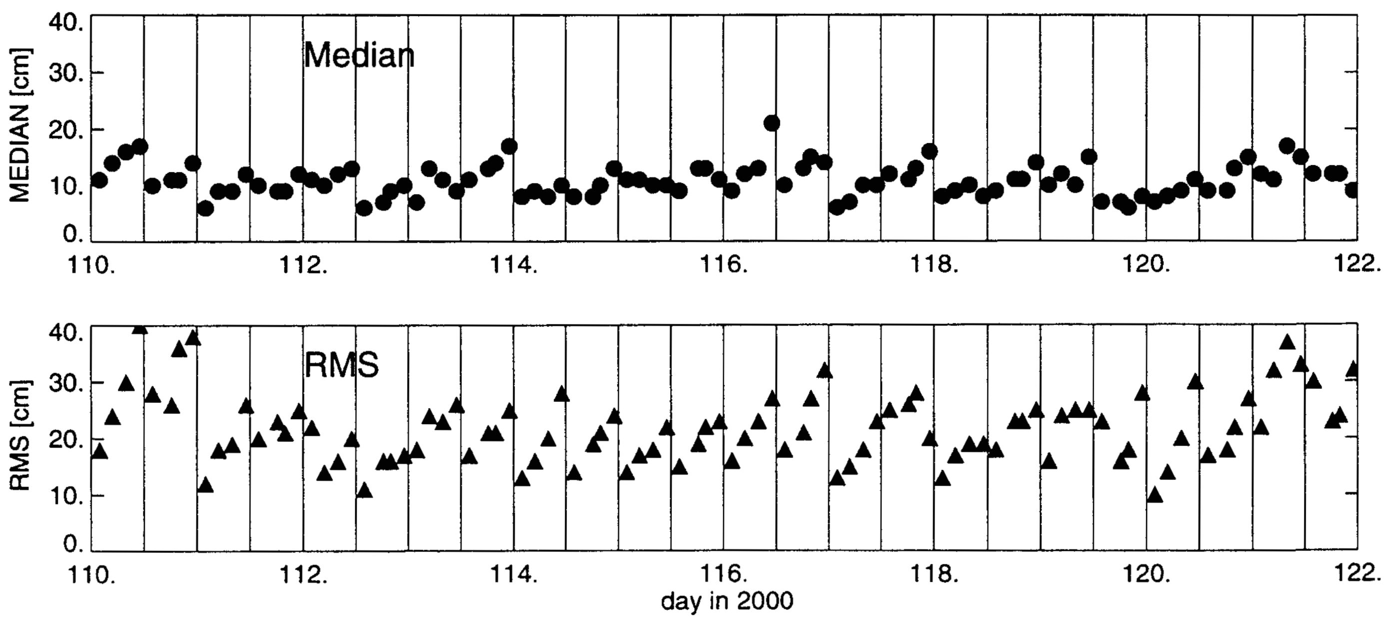

Fig. 6. The quality of orbit predictions (GFU) in bins of 3 hours (0-3,3-6,6-9,9-12) is given for selected days.

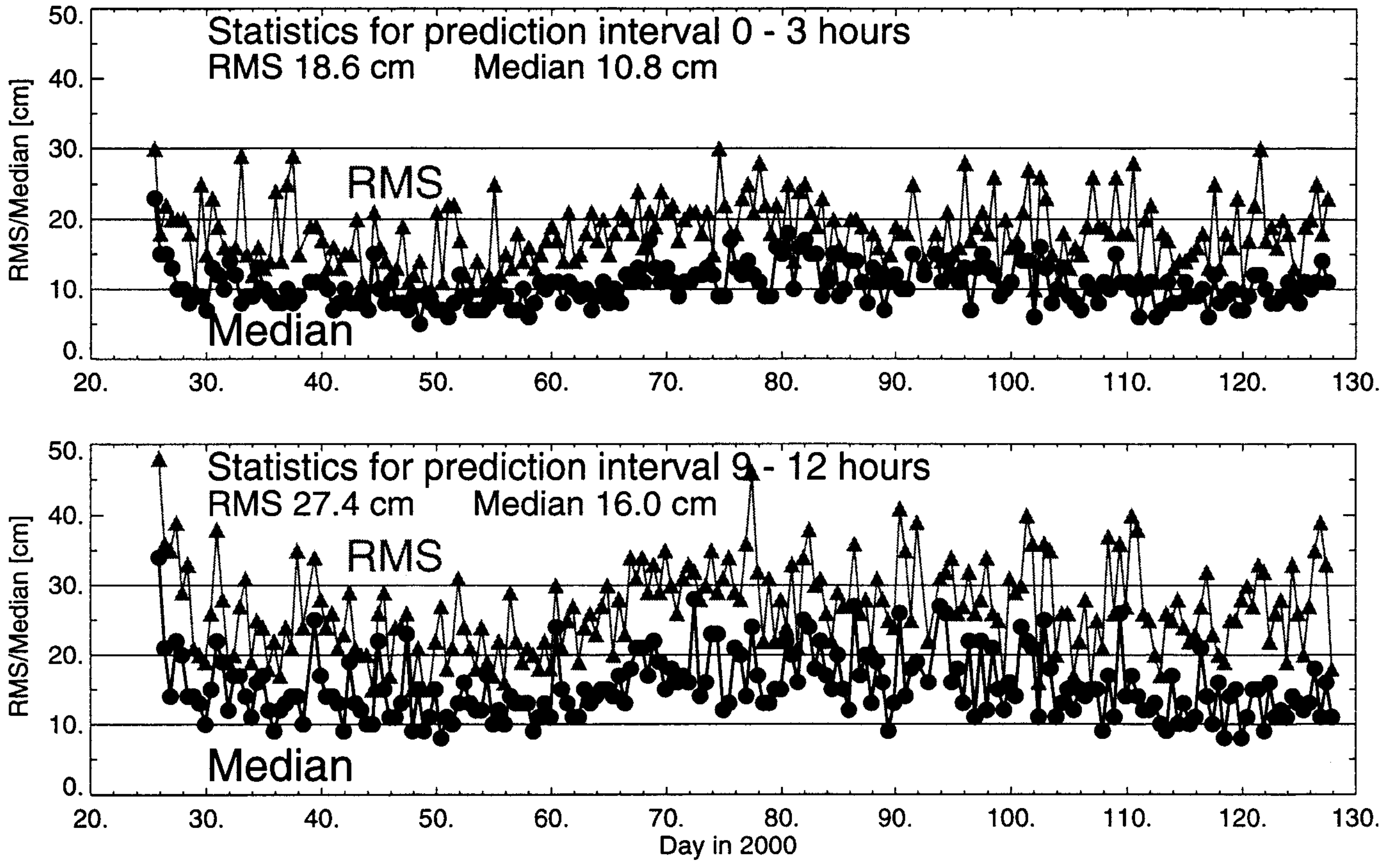

Fig. 7. The quality of orbit predictions is given for the interval 0-3 hours and 9-12 hours.

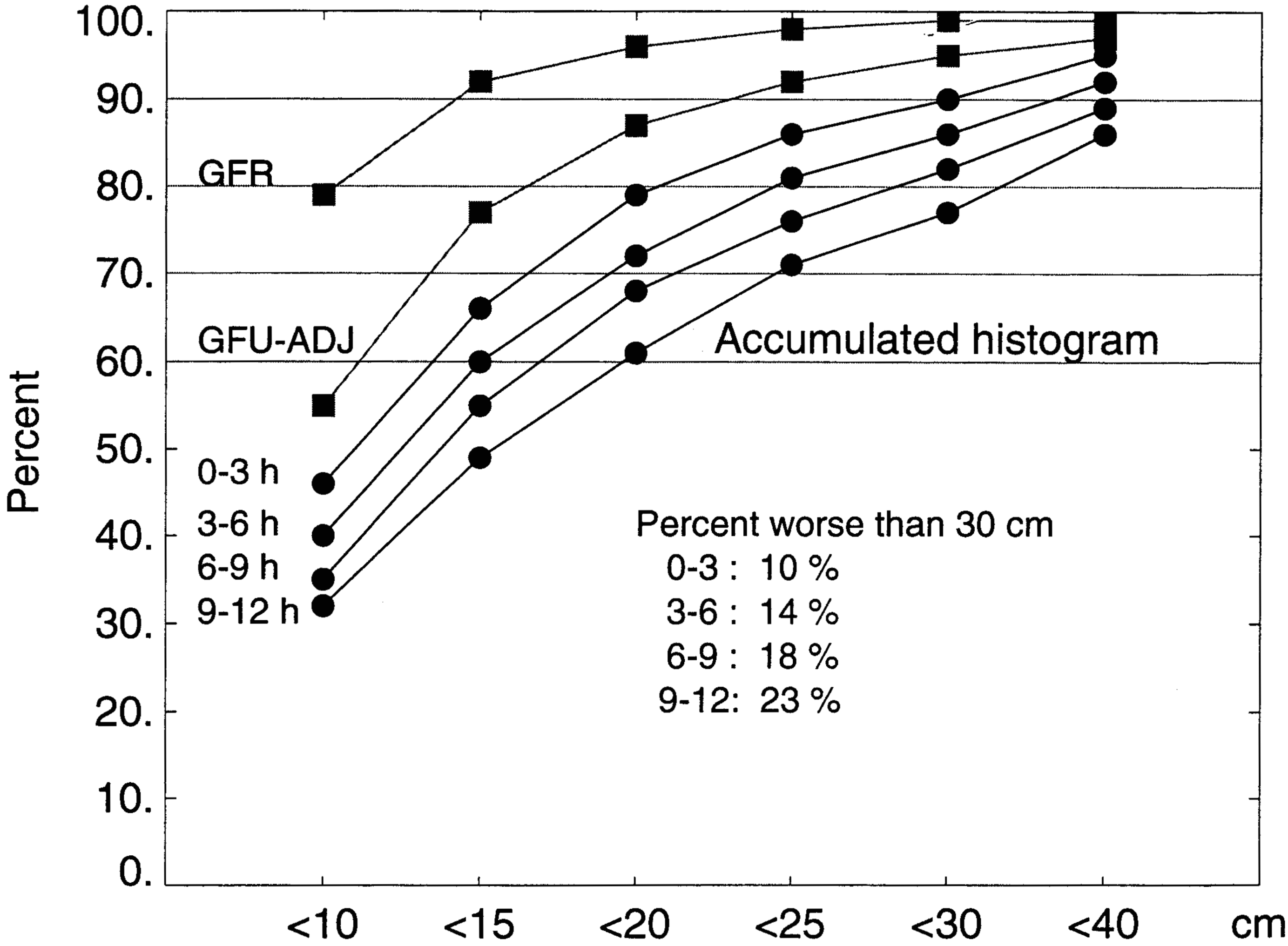

Fig. 8. Histogram of number of satellites (accumulated) with the given accuracy (in cm) for GFR, GFU-ADJ and various bins for the predictions.

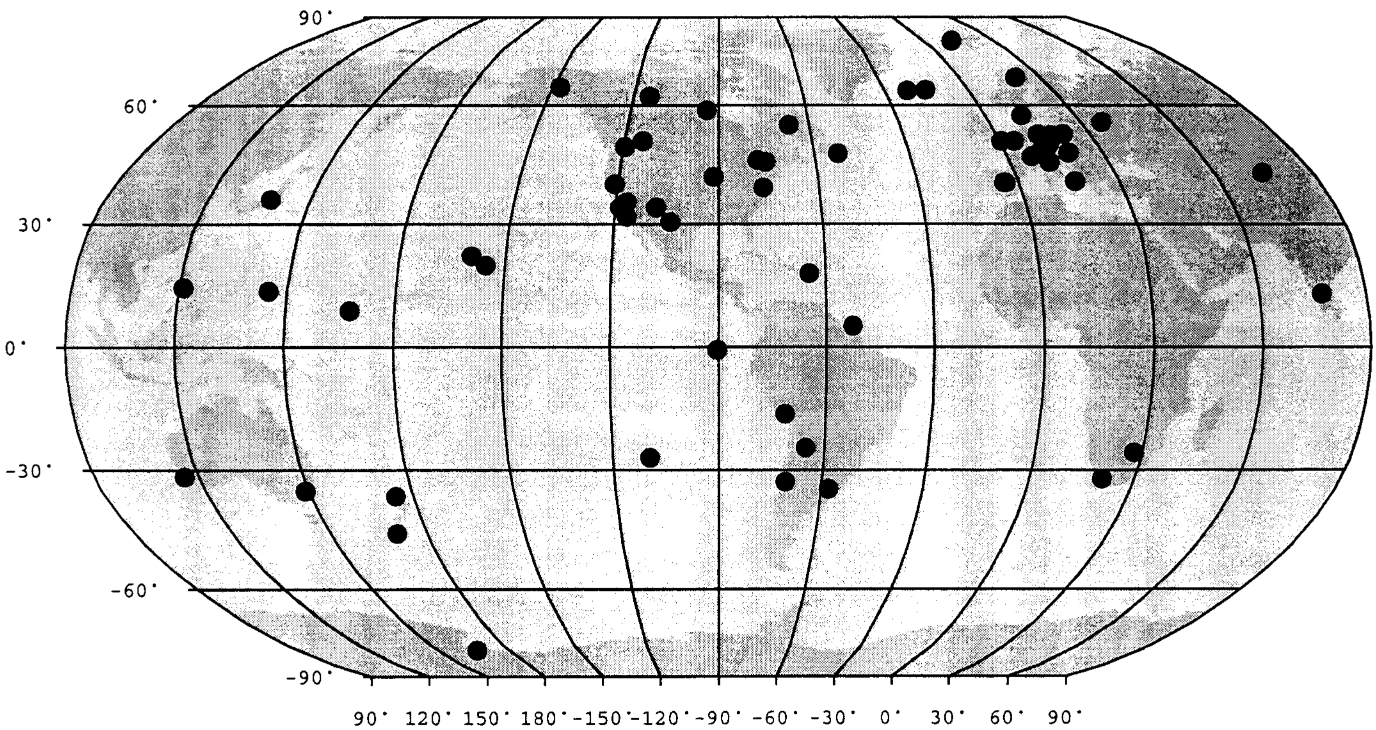

Fig. 9. IGS sites with hourly data.