GPS TIME TRANSFER WITH IMPLEMENTATION OF SELECTIVE AVAILABILITY

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Abstract

The international community of time metrology is facing a major challenge with the Selective Availability (SA) degradation of GPS satellite signals. At present there are 6 Block I satellites and 8 Block II satellites operating. According to the policy of the U.S. Department of Defence the Block I satellite signals will not be degraded, but these satellites are old with a finite life. The Block II satellites, which have all been launched since 1988, were subject to Selective Availability from March 25, 1990. The effect of SA should be to limit precision to about 100 meters for navigation and 167 ns for timing.

A study has been conducted in order to understand the nature of the actual introduced degradation, and to elaborate the means of removing the effects of this degradation on time transfer. This study concerns the time extraction from GPS satellites at NIST, USNO and Paris Observatory, and the comparison of atomic clocks between these laboratories by common view approach. The results show that when using the data taken over several days the time extraction can be achieved with uncertainty of a few tens of nanoseconds, while strict common–view has removed entirely the effects of SA during the periods under study.

INTRODUCTION

Over the past ten years non–degraded GPS satellite signals have become the principal tool for national and international comparisons of atomic clocks. Using GPS, time transfer is now ten times more accurate than it was using LORAN–C. The introduction of GPS has led to a major improvement of world wide time metrology in precision, accuracy and coverage. With GPS, time comparisons are performed with an accuracy of a few nanoseconds for short baselines (up to 1000 km) and 10 to 20 nanoseconds for intercontinental distances. This makes it possible to compare the best standards in the world at their full level of performance: for integration times of only 10 days, the frequency differences between atomic clocks are measured at the level of one part in 1014. The most recent studies[1, 2] show further improvements.

Thus, GPS has brought a major contribution to such activities as the establishment of International Atomic Time (TAI), the realisation of the NASA's JPL Deep Space Network (DSN) and the studies of millisecond pulsars. All this was done with an undegraded GPS, free of Selective Availability.

Unfortunately, since the GPS concept was born in 1973, different ways to prevent civil users having access to the entire accuracy of the system have always been under consideration[3, 4]. The type of degradation of GPS signals, called Selective Availability (SA), have now been approved. On the 25th of March 1990 SA was officially implemented on Block II satellites. The effect of SA should be of about 167 ns for timing.

The 6 Block I satellites are not affected by SA but they are old and in 1993, when GPS will be declared fully operational, these satellites will probably be turned off and the whole constellation will be composed of Block II satellites, all affected by SA. Does this represent a disaster for time metrology and the return to LORAN–C epoch? Perhaps not.

The SA affects direct access to GPS time most severely. This access is degraded by a factor of up to ten. Even with SA, however, the GPS time is distributed with uncertainty better than 1 microsecond which is satisfactory for many non–metrological applications. In addition, as this study shows it, a smoothing over a period of several days removes most of the SA effects, and reduces the uncertainty of access to GPS time to several tens of nanoseconds.

One major problem could be the impact of SA on high accuracy time comparisons. Here again an appropriate treatment of data can entirely remove the degradation of the GPS signal. The realisation of a strict common–view between two laboratories (synchronization of observations within 1 second) completely removes the phase jitter of satellite clock. The elimination of the impact of ephemerides degradation is much more arduous: this requires delayed access to precise ephemerides for correcting the degraded broadcast ephemerides.

Yet, the official implementation of SA has reserved us two pleasant surprises: as this study shows, the broadcast ephemerides appear not to be degraded, and on the 10th of August 1990 SA was removed from Block II satellites.

DEGRADATION OF GPS SIGNALS

The degradation of GPS signals is linked with the history of the development of GPS. At first the project was no more than the reservation of P–code for authorized users with ultimate uncertainty of real–time positioning of 16 m. It was intended that C/A–code would be accessible to all users and would have a capacity of 100 m for real–time positioning. After the launch of first GPS satellites it became clear that the performance of C/A–code is much better than expected: instead of the announced 100 m uncertainty, users equipped with cheap C/A–code receivers were able to easily obtain 30 m. This has lead the DoD to review its policy concerning availability of GPS to the general public.

The concept of Selective Availability was born with the intention of degrading the positioning accuracy for Standard Positioning Service (SPS) users to 120 m[3]. All Block II satellites are subject to SA. In addition to SA, an Anti-Spoofing (A–S) mode of operation can be activated. This is a method of protecting military operations against adverse imitations of P–code by encryption of P–code. The encrypted P–code is denoted Y–code. The A–S does not affect C/A–code. Receivers equipped with the utility to remove the effects of S/A and A/S are called Precise Positioning Service (PPS) receivers.

According to the information accessible to the civil community, SA should consist of:

1. a phase jitter of the satellite clocks, the effect of which can be removed by a strict common view for time transfer, and
2. a changeable bias in the broadcast ephemerides.

The net of the two SA effects is about 100 meters for navigation and 167 ns for timing. Some of the bias in the ephemerides will cancel in common view. The smaller the baseline the more the cancellation.

Since the concept of limiting access to P–code to PPS users only was withdrawn and SA was introduced instead, P–code receivers have became available on the market for the general public. However these owners of P–code receivers are unable to eliminate the errors added by SA to GPS signals; the only advantage they keep is that of using two frequencies L1 and L2 in the codeless mode to measure ionospheric delay. The PPS users remove degradation by employing SA decription techniques. Table I and II give the approximate performances of GPS in terms of the information available to the civil community.

Table I. Effects of SA on positioning

OPERATING MODE		PPS USERS		SPS USERS	
SA	A–S	P(Y)–CODE	C/A–CODE	P–CODE	C/A–CODE
OFF	OFF	16 m	30 m	16 m	30 m
ON	OFF	16 m	30 m	100 m	120 m
OFF	ON	16 m	30 m	?	30 m
ON	ON	16 m	30 m	?	120 m

Table II. Effects of SA on the dissemination of *GPS time*

OPERATING MODE		PPS USERS		SPS USERS	
SA	A–S	P(Y)–CODE	C/A–CODE	P–CODE	C/A–CODE
OFF	OFF	15 ns	40 ns	15 ns	40 ns
ON	OFF	15 ns	40 ns	142 ns	167 ns
OFF	ON	15 ns	40 ns	?	40 ns
ON	ON	15 ns	40 ns	?	167 ns

We have observed in the past several exercises which might have been the tests of SA. Here we give a brief description of them together with the officially implemented SA.

A) Exercise of September 29 to October 2, 1989. During these 4 days the signals of Block I satellites were perturbed. This exercise, which may have been a test of SA showed a phase jitter of the satellite clocks and a degradation of ephemerides. In it,

- the slopes of linear fit to a 13-minute track increased from the usual 15 ps/s to 100 ps/s. These slopes were different for simultaneous observations in different laboratories. For example, for PRN 13 observed on September 29, 1990 at 19h18m UTC, the slope was of −105 ps/s at OP and −26 ps/s at NIST. This would indicate a bias in ephemerides,
- the comparison by common-view of UTC(OP) with UTC(PTB) (distant of about 700 km) had a standard deviation of 15 ns instead of the usual several nanoseconds, but comparison of UTC(OP) with UTC(NIST) (distant of about 7500 km) had a standard deviation of 100 ns instead of the usual 15 ns. This indicates an error in ephemerides which can partially be cancelled over short distances.

B) Exercises on PRN 14. During several months before implementation of SA the first satellite of Block II, PRN 14 was submitted for short times to degradation which seemed to consist only in phase jitter.

C) "March—August 1990" Implementation of SA. On March 25, 1990 all satellites of Block II were subjected to Selective Availability (see Fig. 1). The discrepancy of UTC(USNO) — GPS time values has increased by a factor of ten. As during the exercise of September 29 — October 2, 1989 the slopes of 13-minute tracks have increased by approximately the same amount. However the slopes were quite similar for simultaneous observations from different laboratories. For example, for PRN 14 observed on March 30, 1990 at 6h30m UTC, the slope was −107 ps/s at OP and −113 ps/s at USNO. The slight difference between these two slopes is certainly due to local conditions of observations such as multipath propagation, rather bad estimation of ionospheric delays. ... Moreover, the common-view comparisons entirely removed the SA. This means that the SA consisted manly of a phase jitter of satellite clocks without ephemeride degradation. The SA introduced on March 25 was suspended between June 24 and 30, July 8 and 14. On August 10, 1990 it was removed and has not yet, at the time of the meeting, been reimposed.

DISSEMINATION OF TIME

The GPS is primarily a tool of time dissemination. Many users employ the GPS to acquire GPS time or UTC for use in real time or in post-processing. Real-time access to GPS time can easily be realized with an uncertainty of 100 ns when SA is off. With some post-processing this value can be considerably reduced.

What happens when SA is activated can be seen on Fig. 1. Real-time access to GPS time by a single space vehicle can be realized with an uncertainty of several hundreds of nanoseconds. This is satisfactory for some applications. A more accurate access to GPS time can be obtained with postprocessed smoothed data. The results depend of the length of the smoothed period. From the results given by Table III we can conclude that the effects of SA on time dissemination can be reduced to the level of 30 ns when smoothing (Vondrak smoothing[9] the data over 10 days (see also Fig. 2). Smoothing over 1 day gives about 100 ns and over 3 days about 50 ns. Moving average of one day and three days provides similar results.

ACCURATE TIME COMPARISONS VIA COMMON VIEW

In time metrology there is a need for accurate comparisons of remote atomic clocks. Ideally the method of comparison employed should not obscure the performance of the clocks. The simultaneous observations of GPS satellites, known as the common-view approach, has proved to be very close of this ideal[1, 2, 5]. Moreover during the implementation of SA, precisely synchronised common-views entirely remove the effects of satellite clock phase jitter. The common-view approach also reduces the effect of ephemeride degradation[6].

During this study for Block II satellites we used strict common-views with synchronization to 1 second (assuming that both receivers use the same reference time for monitoring the tracks), and the tracks of the full standard length of 13 minute. We have used raw data with no correction for broadcast ephemerides or ionospheric model. The antennas coordinates were corrected [7,8]. The values of UTC(OP)−UTC(USNO) are smoothed (Vondrak smoothing[9]) over the periods of ten days. The results are given by Table IV, and are illustrated by Fig. 3.

Clearly, strict common-views completely eliminate the effects of SA, which means that there is no ephemeride degradation. The distance between OP and USNO being about 6000 km, a large error in ephemerides would introduce a major discrepancy. The slight difference, a few nanoseconds, between the results of Block I and Block II comes from the use of different ensembles of satellites. This can be the effect of broadcast ephemerides, model of ionosphere, multipath propagation...

The results of another common-view comparison of two distant laboratories (OP and NIST) during implementation of SA can be found in[2].

CONCLUSIONS

This study shows that the March—August 1990 implementation of SA consisted only of satellite clock phase jitter, and can be entirely removed by strict common-views. The satellite ephemerides were not degraded. This is fortunate for time metrology, and brings the hope that even degraded GPS signals will allow high accuracy time comparisons without painful and time-wasting correction of ephemerides.

At present, however, there is no certainty that SA will continue to be implemented in this way. The exercise of September 29—October 2 1989 shows that the degradation of ephemerides is possible. For this reason the community of time metrology is well-advised to continue its efforts in studying possible techniques for the correction of degraded ephemerides. Various approaches are now being considered [6]. These include the use of precise ephemerides or the use of the differences between broadcast undegraded and broadcast degraded ephemerides if provided by OCS. At present the delay of three months with which precise ephemerides are accessible is a major obstacle to their use on an operational basis. Additionally, the use of precise ephemerides requires the record of broadcast ephemerides in some laboratories around the world (one per area). At present the broadcast ephemerides are recorded regularly at BIPM (Sèvres, France) and NIST (Boulder, Colorado).

The implementation of SA is a severe drawback in terms of direct access to time, but for delayed dissemination of time the effects of SA can be considerably reduced.

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LIST OF ACRONYMS AND ABBREVIATIONS

A–S	Anti–Spoofing
BIPM	Bureau International des Poids et Mesures
CV	Common–View
C/A–Code	Coarse/Acquisition Code
DoD	United States Department of Defence
GPS	Global Positioning System
JPL	Jet Propulsion Laboratory
OCS	GPS Operational Control Segment
OP	Paris Observatory
NASA	National Aeronautic and Space Agency
NIST	National Institute of Standards and Technology
P–Code	Precision Code
PPS	Precise Positioning Service
PTB	Physikalisch–Technische Reichsanstalt
SA	Selective Availability
SPS	Standard Positioning Service
SV	Space Vehicle
USNO	US Naval Observatory
UTC	Coordinated Universal Time

Table III. 10-days smoothed values of UTC(k) - *GPS time*.
Unit: 1 nanosecond.

UTC(OP) - *GPS time*

Date 1990	By Block I 28 SV	By Block II 64 SV	Block I -Block II	SA on Block II
May 18	-318	-352	34	ON
May 28	-252	-266	14	ON
June 7	-141	-135	-6	ON
June 17	-12	-21	9	ON
June 27	116	112	4	ON
July 7	123	98	25	ON
July 17	-16	15	-31	ON
July 27	-137	-126	-11	ON
Aug. 6	-162	-137	-25	ON
Aug. 16	-92	-96	4	OFF
Aug. 26	27	33	-6	OFF

UTC(USNO) - *GPS Time*

Date 1990	By Block I 45 SV	By Block II 12 SV	Block I -Block II	SA on Block II
May 18	-105	-111	6	ON
May 28	-52	-88	36	ON
June 7	28	0	28	ON
June 17	128	142	14	ON
June 27	232	232	0	ON
July 7	254	238	16	ON
July 17	111	115	-4	ON
July 27	-40	-34	-6	ON
Aug. 6	-120	-120	0	ON
Aug. 16	-118	-118	0	OFF
Aug. 26	-38	-33	-5	OFF

Table IV. UTC(OP) - UTC(USNO) by common-view.
Unit: 1 nanosecond.

Date 1990	by Block I 7 CV	by Block II 3 CV	Block I -Block II	SA on Block II
Mar. 9	-790	-788	-2	OFF
Mar. 19	-706	-709	3	OFF
Mar. 29	-577	-574	-3	ON
Apr. 8	-485	-482	-3	ON
Apr. 18	-410	-410	0	ON
Apr. 28	-365	-365	0	ON
May 8	-296	-293	-3	ON
May 18	-213	-215	2	ON
May 28	-215	-211	-4	ON
June 7	-171	-169	-2	ON
June 17	-160	-157	-3	ON
June 27	-140	-140	0	ON
July 7	-148	-149	1	ON
July 17	-144	-147	3	ON
July 27	-112	-111	-1	ON
Aug. 6	-61	-58	-3	ON
Aug. 16	-6	-5	-1	OFF
Aug. 26	-51	-48	-3	OFF

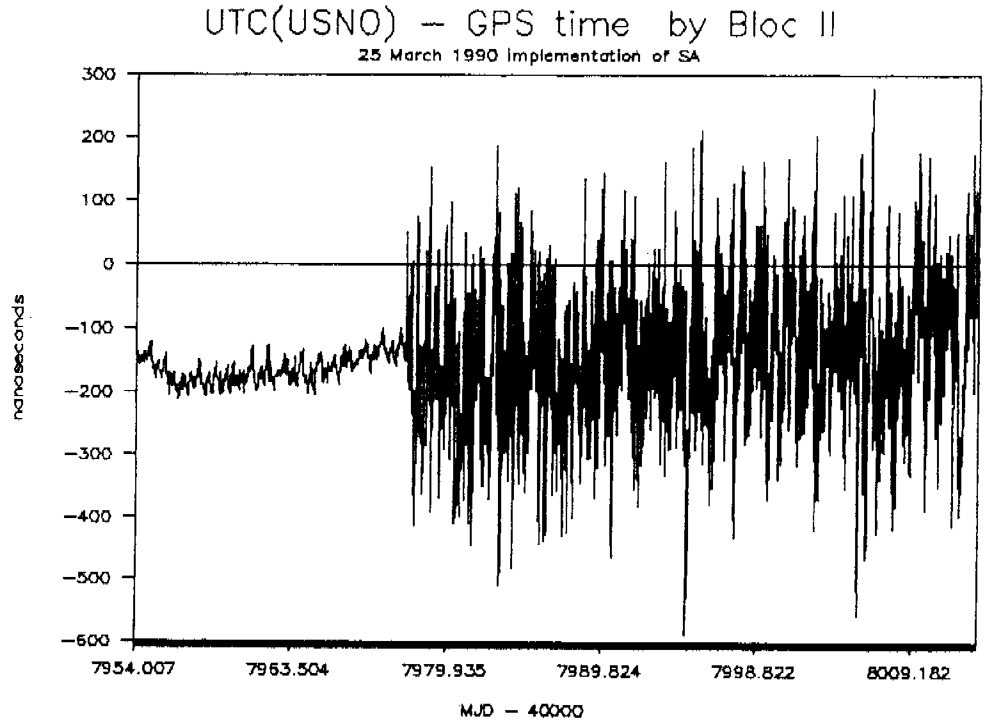

Figure 1. Implementation of SA on 25 March 1990 as seen from the US Naval Observatory.

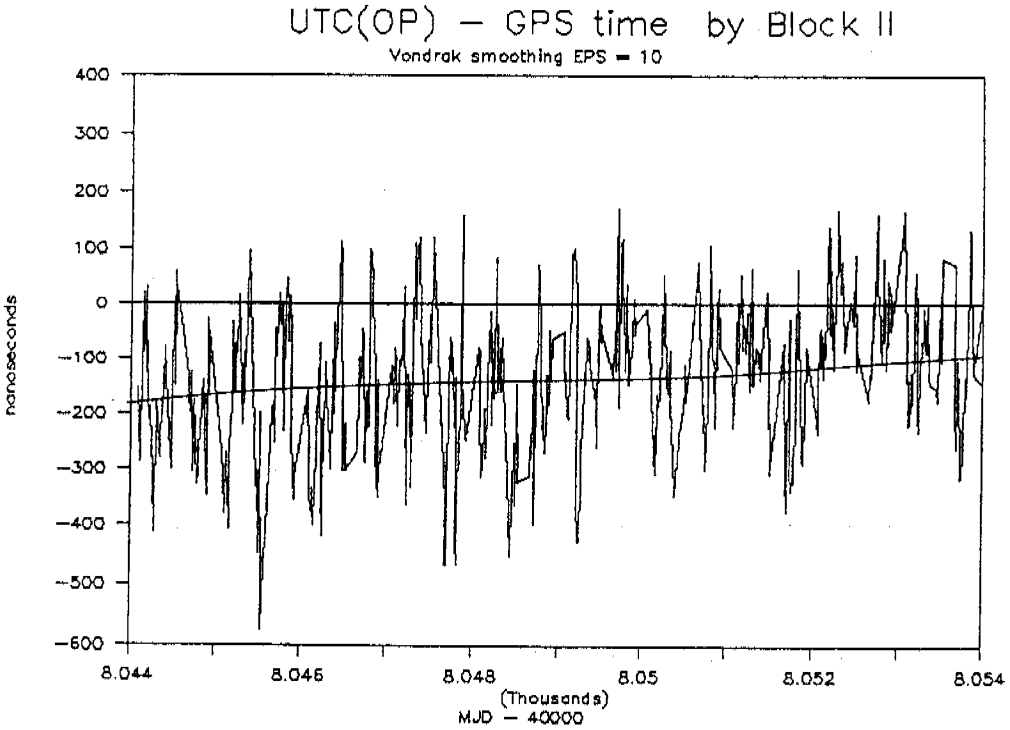

Figure 2. Values of UTC(OP)-GPS time by Block II satellites smoothed over a periode of 10 days.

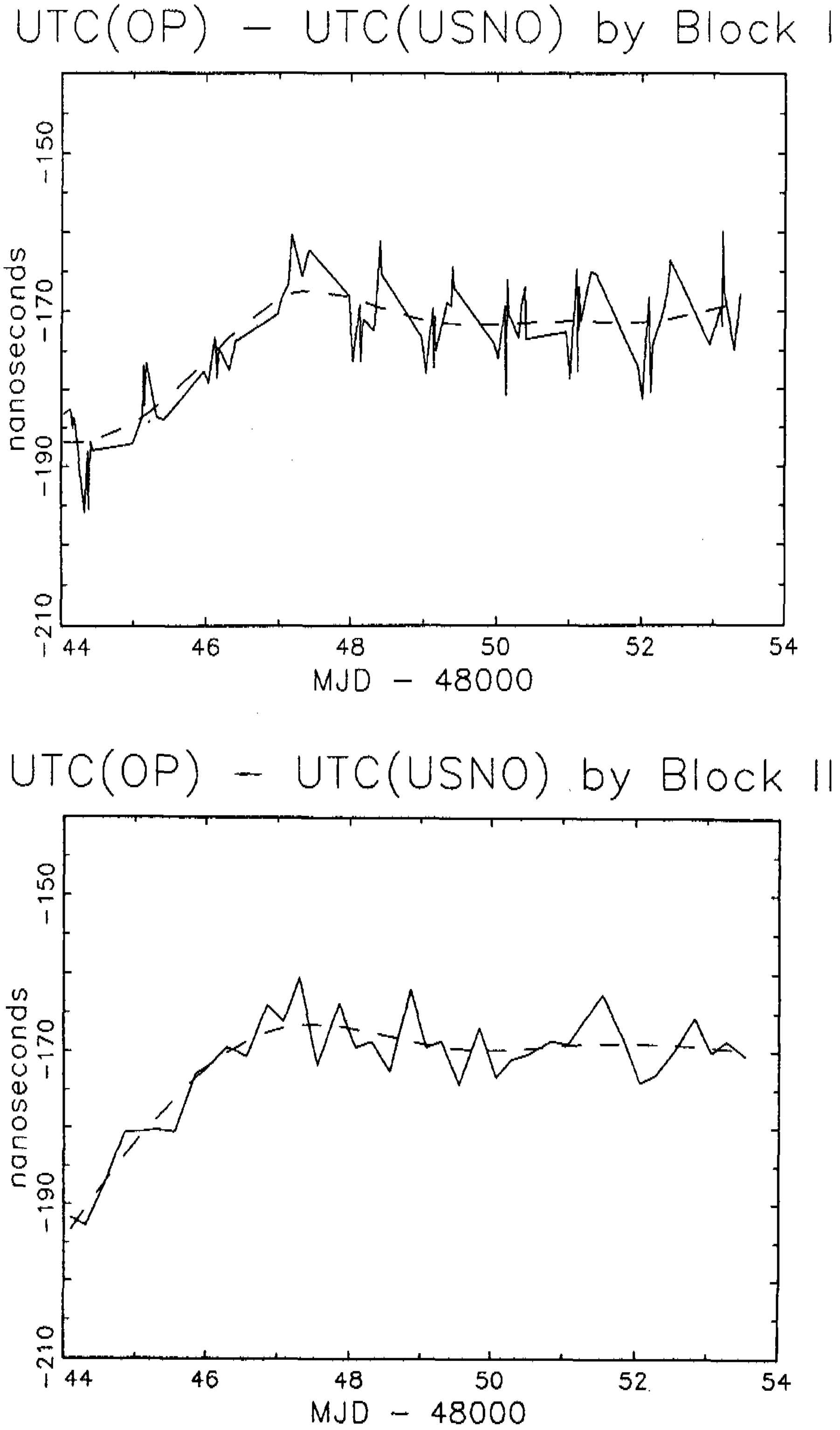

Figure 3. **Common-views between Paris Observatory and US Naval Observatory (distante of about 6000km) over a periode of 10 days. Dashed lines represent smoothing.**

QUESTIONS AND ANSWERS

Unidentified Questioner: What smoothing algorithm did you use?

Mr. Lewandowski and David Allan: The data that you saw used Vondrak smoothing before the SA, but the actual smoothing on the one day, three day and ten day samples was just simple averaging.

Dr. Gernot Winkler, U.S Naval Observatory: The noise is not white, and it is not Gaussian. Under these conditions, averages are not the optimum estimator of the center of the distribution. I have made some tests using simply the median of neighboring values, and if you have sufficient numbers of observations, and of course we will have more with more satellites, this becomes much more effective.

Professor Carroll Alley, University of Maryland: Is there any evidence of periodicity in the noise? What is the shortest time between which you can do these comparisons?

Mr. Lewandowski: The time between observations was 30 minutes. We were just looking for common view time comparisons.

Unidentified Questioner: In view of the political environment, is there any change in the SA policy?

Mr. Lewandowski: No one knows! At least they are not saying!