PRECISE EPHEMERIDES FOR GPS TIME TRANSFER

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Abstract

The present technology of atomic clocks motivates time transfer techniques with nanosecond accuracy. Global Positioning System (GPS), the most common means for international time comparisons could achieve such accuracy over short distances (up to 1000 km). Over intercontinental distances the accuracy of the GPS time transfer ranges between 20 and 30 ns. Some of the principal error sources are the broadcast ephemerides, the broadcast ionospheric model, and the local antenna coordinates. This study investigates the quality of broadcast ephemerides by comparing them with precise ephemerides and by using precise ephemerides for time transfer. Another aspect of this work is to suggest a strategy to overcome the planned degradation of GPS satellite messages via Selective Availability (SA).

INTRODUCTION

The use of the Global Positioning System (GPS) for international time comparisons is continuously improved by adoption of more accurate antenna coordinates, introduction of double frequency ionospheric calibrators, organization of differential calibrations of receivers and refinement of data processing. This study examines the impact of the error in satellite position from the use of broadcast ephemerides on common–view time transfer[1].

Table 1 demonstrates the impact for the most unfavorable case, when a bias in satellite position is parallel to the baseline between two timing centers. For a baseline of 9000 km (Europe–Japan) a bias of 15 m will introduce an error of 43 ns in time transfer using a single common–view measurement. Of course in practice a time comparison between two laboratories is realized by an averaging of a number of common–view measurements and so this error is reduced.

The quality of broadcast ephemerides over a two month period was studied in two ways: a direct comparative study of broadcast versus precise ephemerides, and a comparison of common view transfer using broadcast versus precise ephemerides.

The precise ephemerides used in this work were produced by the Naval Surface Warfare Center (NSWC); the broadcast ephemerides were recorded in Wettzel (Federal Republic of Germany).

Error in satellite position can be a major problem during the future implementation of Selective Availability (SA); the use of precise ephemerides and other possible ways of facing this challenge are discussed.

BROADCAST EPHEMERIDES

The GPS broadcast ephemerides are computed by the Air Force Operational Control Segment (OCS). The OCS has global tracking and monitor stations located at:

- -Falcon (U.S.A., Colorado Springs, Long.= 255.5 deg. E, Lat.= 38.5 deg. N),
- -Kwajalein Island (U.S.A., Pacific Ocean, Long.= 167.3 deg. E, Lat.= 9.1 deg. N),
- -Ascension Island (Great Britain, Atlantic Ocean, Long.= 345.8 deg. E, Lat.= 7.6 deg. S),
- -Diego Garcia Island (Great Britain, Indian Ocean, Long.= 72.2 deg. E, Lat.= 6.3 deg. S),
- -Hawaii (U.S.A., Pacific Ocean, Long.= 202.5 deg. E, Lat.= 20.5 deg. N).

Multichannel double frequency receivers are deployed at each of these sites to allow all satellites in view to be tracked simultaneously. Performed measurements are pseudo–range, Doppler, and ionospheric delay.

Data are sent in real time to the master control station for use in the Kalman filter which estimates the clock and orbit states for each satellite. These states are used to upload information to the satellites, which they in turn transmit to users. The ephemerides are among these broadcast data.

The orbit states in the Kalman filter for a given satellite are estimated as corrections to a reference orbit. The reference orbit is based on previous data and predicted once per week for the next week. With a reference orbit thus established, the tracking data are used to improve the orbit, and compute corrections to the reference orbit once every 15 min.

When an upload is required, the most recent corrections to the reference orbit are applied linearly to predict the next two weeks of ephemerides. The information in the upload consists of fourteen days of one–pages, though normally a new upload is done at least once a day. A satellite transmits a new page of parameters during each hour. Each one–hour page is the first hour of a fit optimizing parameters to four hours of estimates of the satellite orbit from the Kalman filter. The reference time for this fit is in the center of the four hours. Thus, a satellite transmits the same parameters for an hour, and these parameters are actually good for four hours.

The frequency of uploads is driven by a 6 meter User Range Error (URE). The actual time of an upload is decided by a number of considerations such as URE, location of satellite, and availability of the uplink. Currently the OCS is uploading the GPS satellites 1 to 3 times per day. It can happen that an upload does not improve the URE, in which case it can be immediately followed by another.

PRECISE EPHEMERIDES

The GPS precise ephemerides and clocks were computed at the Naval Surface Warfare Center (NSWC) from the beginning of 1986 until the GPS week 498 ending July 29, 1989. Since GPS week 499, July 30, 1989, they have been computed at the Defense Mapping Agency (DMA). The block II satellites are not yet included in the precise ephemerides computations.

The pseudo–range measurements used for the computations of precise ephemerides are performed at ten tracking stations[8]. Five of the stations are the Air Force's OCS monitoring stations mentioned in the previous paragraph. The other five stations are operated by DMA and are located in:

- - Australia (Long.= 138.7 deg. E, Lat.= 34.7 deg. S),
- - Argentina (Long.= 301.5 deg. E, Lat.= 34.6 deg. S),
- - England (Long.= 358.7 deg. E, Lat.= 51.5 deg. N),
- - Bahrain (Long.= 50.6 deg. E, Lat.= 26.2 deg. N),
- - Ecuador (Long.= 281.5 deg. E, Lat.= 0.2 deg. S).

A 4–channel double–frequency receiver is deployed at each of these stations. The receivers are driven by high performance cesium frequency standards. The minimum observation angle for observation is 10 degrees. Temperature, pressure, and humidity are recorded at each site. The range measurements are corrected for ionospheric delay (two–frequency first order correction), tropospheric refraction (Hopfield model), periodic relativistic effects, offset between center of phase of antenna and center of mass of satellite (about 1 meter), and station displacements due to earth tides. The range observations collected at a 1.5 s rate are smoothed using carrier phase, in order to give 15 min of smoothed range observations. An observation standard deviation of 75 cm is assigned to each smoothed pseudo–range.

The DMA and the OCS monitor stations use essentially identical procedures for data collection and smoothing. These smoothed pseudo–range data are used as an input to the OMNIS Multisatellite Filter/Smoother software using the Kalman filter[9,10]. The computations are done in one hour batches processing simultaneously eight days of data of all stations and all satellites. The eight days allow one–half day overlaps with consecutive weeks.

Reference trajectories for all satellites are integrated using a truncated WGS 84 Earth Gravity Model (degree 8, order 8), mass gravity fields for the Sun and Moon, solid Earth tides, the Rockwell Rock4 model of radiation pressure including acceleration perpendicular to the direction of the sun, nutation, Earth rotation, UT1–UTC (using DMA initial values generated the week before the orbit fit), and a 5 min integration step.

Each weekly fit estimates:

- -for each satellite: orbital elements, radiation pressure modelled stochastically including acceleration perpendicular to the sun, and clock parameters,
- -for each monitor station, station clock parameters,
- -polar motion and UT1–UTC modelled as random constants.

The above described procedure generates fitted trajectory and clock files containing:

- -for every 15 min the position of the center of mass of each satellite expressed in WGS 84 coordinate system (X, Y, Z in km, DX/DT, DY/DT, DZ/DT in km/s, GPS time in year, month, day, hour, minute),
- -at one–hour intervals the time and frequency offsets between each satellite's clock and GPS time and frequency.

The uncertainty of precise ephemerides ranges from 1 m to 5 m.

COMPARISON BETWEEN BROADCAST AND PRECISE EPHEMERIDES

Although it is not the main purpose of this paper to examine differences between broadcast and precise ephemerides, we present the results of a comparison study which are necessary for further analysis. The sample of data we examine starts February 29, 1988 and ends April 23, 1989. The broadcast ephemerides were provided by the National Geodetic Survey (NGS). They were recorded in Wettzel (West Germany) as Keplerian parameters for each satellite for every hour of satellite visibility. The precise ephemerides come from NSWC and are presented as described at the end of the previous paragraph.

The satellite positions expressed in precise and broadcast ephemerides are compared in radial, on–track, and cross–track components at the time of the recording of the broadcast ephemerides. We have about seven comparisons per day for each satellite. Comparisons are made for all 53 days of the examined period in two intervals: Feb. 29 to March 31, 1988 and April 1–23, 1988. This has been done to separate the eclipse seasons.

During each year there are two periods when a given GPS satellite enters the Earth's shadow on every revolution. During these eclipse seasons larger thermal variations occur within the spacecraft than the rest of the year and accordingly may cause larger clock frequency variations. These variations are removed during the production of precise ephemerides, but they are not removed during the generation of broadcast ephemerides and may have a direct impact on their quality. In 1988 the eclipse seasons were the following: February 18–March 31, August 14– September 25, for PRN6/NAV3, PRN9/NAV6 and PRN12/NAV10; January 10–February 6, July 5–August 6, for PRN3/NAV11, PRN8/NAV4, PRN11/NAV8 and PRN13/NAV9. Thus for the period we are studying three satellites were in eclipse from Feb. 29 to March 31, 1988.

The results of this comparison are given in Table 2, in the form of quadratic means for radial, on–track, and cross–track components. We can observe first that satellites equipped with cesium clocks had broadcast ephemerides differing from precise by only a few meters, even for the eclipse period of PRN12/NAV10. Second, satellites using rubidium clocks had much larger differences, mainly during the eclipse periods. PRN6/NAV3 particularly, had very poor broadcast ephemerides during the eclipse period. PRN9/NAV6 did not exhibit the same degradation of broadcast ephemerides during its eclipse. PRN9/NAV6 had a cesium clock on board whereas PRN6/NAV3 did not. This cesium clock, though not in use, may have provided thermal mass, thus decreasing daily thermal variations. The two satellites were operating the same kind of rubidium clock. PRN8/NAV4 using a quartz oscillator has ephemerides comparable to spacecrafts using rubidium clocks.

Another study of the comparison of broadcast and precise ephemerides with an emphasis of geodetic differential positioning can be found in[6].

BROADCAST EPHEMERIDES AS USED BY A TYPICAL GPS TIME RECEIVER

There is an internationally agreed–upon format for the collection and transmission of GPS time data, as used by the BIPM. A GPS time receiver collects data during its 13 min period. The received broadcast message contains, among other information, Keplerian orbital parameters and their perturbations. The 13 min tracks are determined by a tracking schedule issued by the BIPM.

First the receiver processes short term raw pseudo–range measurements, smoothing them over a period of seconds (typically 6 or 15) points through use of a second degree fit or phase accumulation (depending of the manufacturer). These short–term smoothed pseudo–ranges are corrected by the geometrical delay, the ionospheric delay, and various other parameters. The geometrical delay is computed from the positions of the satellite and user's antenna, both expressed in WGS 84 X,Y,Z coordinates, after the necessary transformations are performed by the receiver software.

A linear fit of the short–term data is used to reduce the comparison of satellite clock versus laboratory clock over the 13 min track to a slope, an intercept and a standard deviation. These data are reported in the BIPM format. If an upload of new ephemerides occurs during the 13 min track, two different broadcast ephemerides can be used during a single 13 min track.

APPLICATION OF PRECISE EPHEMERIDES TO TIME TRANSFER

To examine the impact of precise ephemerides on time comparisons we have chosen a pair of laboratories separated by a 6000 km baseline, Paris Observatory (OP) and U.S. Naval Observatory (USNO). The criterion chosen for this study is the dispersion of residuals of UTC(OP)-UTC(USNO) obtained from individual common view tracks with respect to the mean over all tracks, after correction for the rates of master clocks. The differences between precise and broadcast ephemerides computed in X, Y, Z coordinates (as defined in WGS 84) are interpolated to the middle of considered tracks, then projected on the direction vectors from laboratories to the spacecraft in order to correct time transfer. If there is an abrupt change of these differences (likely due to an upload of broadcast ephemerides) during interpolation period, the track is not corrected but rather is abandoned.

In the first approach we use observations of all available satellites (except PRN8/NAV4). The results are given by Figure 1. The use of precise ephemerides greatly diminishes the dispersion of residuals during the eclipse period for PRN6/NAV3, PRN9/NAV6, and PRN12/NAV10, but during the period following eclipse the amelioration is only slight.

In the second approach, we use only the observations of the satellites equipped with cesium clocks (Figure 2). In this case there is not observable improvement of time transfer using precise ephemerides. Sometimes the standard deviations of the residuals of the time comparison with precise ephemerides are better than those with broadcast ephemerides, sometimes worse (Fig. 2.c). The PRN12/NAV10 does not seem to be affected by its eclipse period. This experiment confirms the results of our comparative study presented in table 2: broadcast ephemerides of satellites with cesium clocks are very close to the precise ephemerides.

EPHEMERIDES DURING SELECTIVE AVAILABILITY

The international community of time metrology is facing a major challenge with the SA degradation of GPS satellites. A recent experiment of the degradation of messages of Block I satellites (Sept. 29 – Oct. 2, 1989), which might be a test of SA, showed:

1. a phase jitter of the satellite clocks, the effect of which will be removed by a strict common view, and

2. a frequently changeable bias in the ephemerides of about 100 meters, the effect of which in common view is roughly proportional to the distance.

To overcome the problem of degraded ephemerides various approaches are being considered. These include the use of precise ephemerides, the use of the differences between broadcast undegraded and broadcast–degraded ephemerides provided by OCS[1], the dynamical or geometrical[2] determination of orbits by the timing community itself.

If either the timing community could have regular access to precise ephemerides or the community computed its own ephemerides, the following arrangements would be useful:

- -the records of broadcast ephemerides should be organized in a few principal laboratories around the world (one per area),

- -in a computation center the differences between broadcast and precise would be applied to time comparisons (as have been done during this study),

- -to avoid the problem of frequently changeable bias in the degraded ephemerides the software of time receivers should be modified so that during one track only one set of Keplerian parameters would be used, even if a new upload of broadcast ephemerides occurs during this track (section 5).

In the case of orbit determination by the timing community itself, the precise coordinates of GPS antennas are essential. Good differential coordinates for short baselines can be derived from time comparisons themselves[3]. The links with the global terrestrial frame ITRF[6], with few exceptions, are not yet satisfactorily realized.

There is another theoretical possibility[5]. A center computing time comparisons instead of receiving 13 minute tracks from the time laboratories could receive 6 or 15 second smoothed pseudo–ranges as described in section 5. Then, using consistent software, all corrections including that of geometrical delay could be computed using precise ephemerides. The advantage of this approach is the uniqueness of the software, the disadvantage is the difficulty of the procedure.

CONCLUSIONS

Concerning the ephemerides of Block I satellites:

1. Broadcast ephemerides of satellites using cesium clocks differ from precise ephemerides by no more than a few meters.

2. Precise ephemerides do not improve the transfer of time if satellites are equipped with cesium clocks.

3. Broadcast ephemerides of rubidium–equipped satellites differ from precise by less than 15 m outside eclipse seasons, and up to 30 m in the case of PRN6/NAV3, during eclipse seasons.

4. When performing intercontinental GPS time transfer, broadcast ephemerides are sufficient when using cesium–equipped satellites, though the use of precise ephemerides with rubidium equipped satellites is recommended.

Concerning ephemerides during the implementation of SA:

1. Precise ephemerides can resolve the problem of SA orbit degradation, provided that the timing community has regular access to these ephemerides with a delay not exceeding 2 weeks.

2. Differences between broadcast undegraded and broadcast– degraded ephemerides, if released with a delay not exceeding 2 weeks, could be another satisfactory solution for SA orbit degradation.

3. For autonomy the timing community should actively investigate methods of independent orbit determination.

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ACRONYMS USED IN THE TEXT

BIPM	Bureau International des Poids et Mesures (International Bureau of Weights and Measures)
DMA	Defense Mapping Agency.
GPS	Global Positioning System.
IERS	International Earth Rotation Service, Central Bureau, Paris, France.
ITRF	IERS Terrestrial Reference Frame.
NGS	National Geodetic Survey, Rockville, Maryland, USA.
NSWC	Naval Surface Warfare Center.
OCS	Operational Control Segment.
OP	Observatoire de Paris, Paris, France
SA	Selective Availability.
USNO	U.S. Naval Observatory, Washington D.C., USA.
WGS	World Geodetic System.

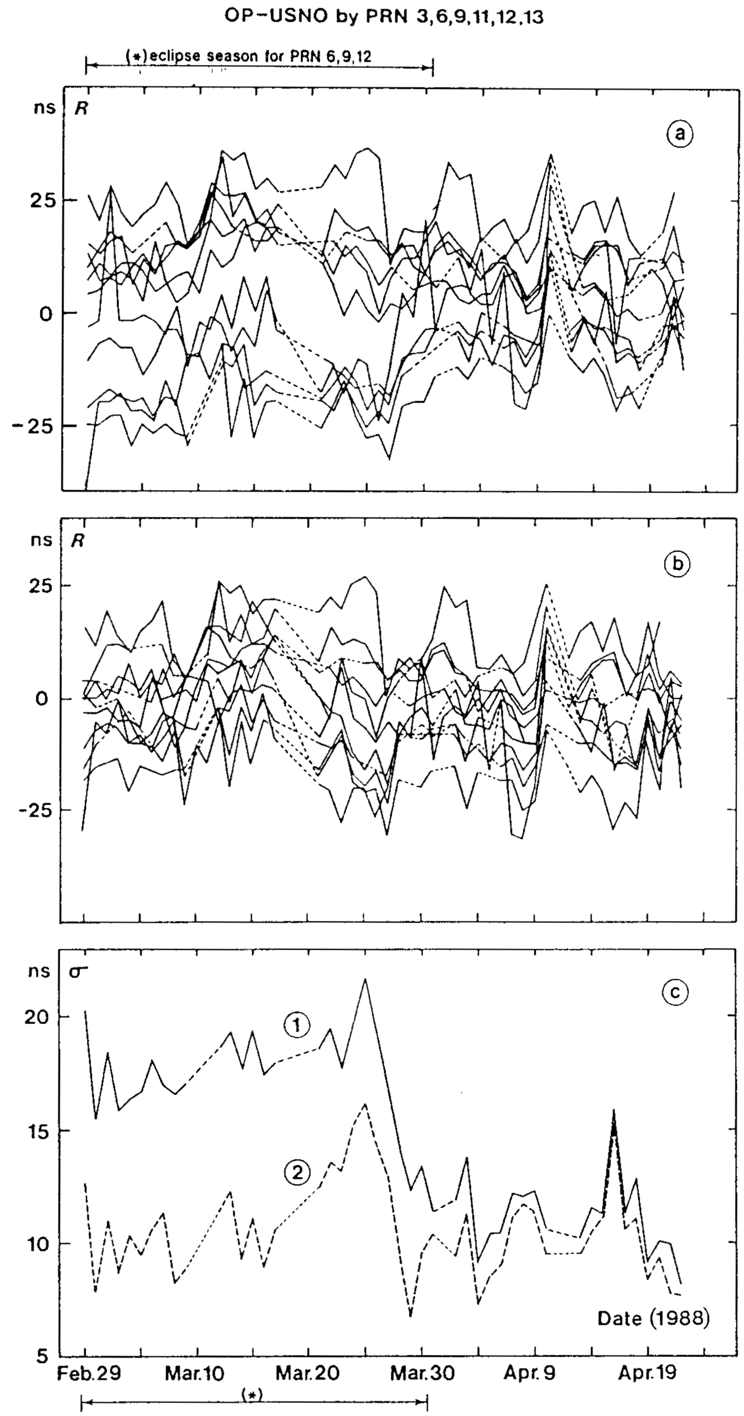

Fig. 1. Residuals (R) of UTC(OP)-UTC(USNO) as given by individual tracks, with respect to the mean (after correction for the rates of master clocks).

(a) - with broadcast ephemerides
(b) - with precise ephemerides

(c) 1 - standard deviations of residuals of (a)
2 - standard deviations of residuals of (b).

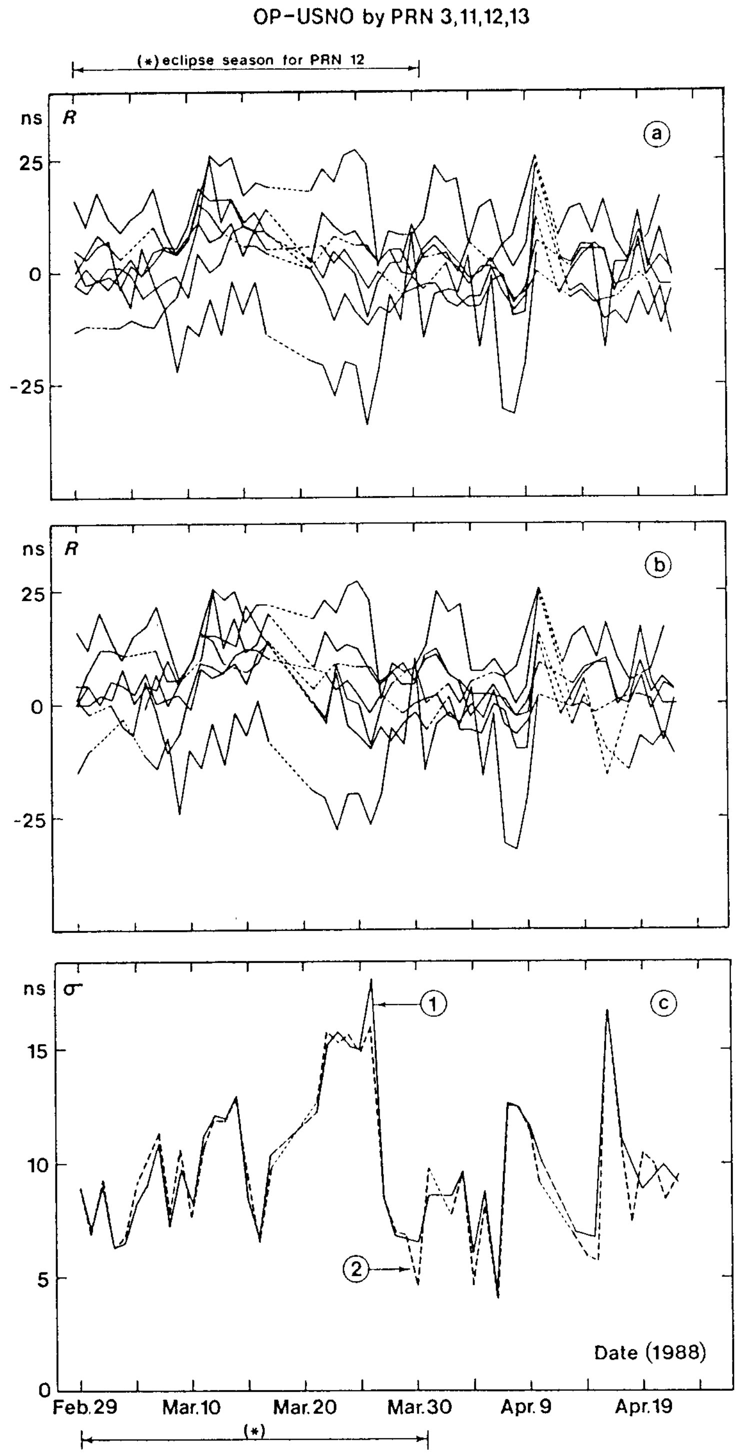

Fig. 2. Same as fig.1 but using only satellites with caesium clocks.

Table 1. Error introduced during a single common view time transfer, by a bias in satellite position parallel to the baseline between two time laboratories.

baseline \ bias	5 m	15 m	30 m	100 m
1000 km	1 ns	2 ns	4 ns	15 ns
3000 km	2 ns	7 ns	14 ns	45 ns
6000 km	4 ns	13 ns	26 ns	89 ns
9000 km	7 ns	20 ns	43 ns	132 ns

Table 2. Quadratic means of precise minus broadcast ephemerides.

Sat. PRN/NAV	Clock	Radial quad. mean (meters)	On-track quad. mean (meters)	Cross-track quad. mean (meters)	Number of points	Comparison interval 1988
3/11	cesium	1.5	3.4	2.2	222	Feb 29-Mar 31
3/11	cesium	1.0	3.3	2.6	161	Apr 1-Apr 23
11/ 8	cesium	2.2	4.2	2.2	262	Feb 29-Mar-31
11/ 8	cesium	1.4	4.6	3.3	175	Apr 1-Apr 23
12/10	cesium	1.2	5.3	3.0	211	Feb 29-Apr 31*
12/10	cesium	0.9	3.1	2.6	133	Apr 1-Apr 23
13/ 9	cesium	1.5	4.0	2.9	232	Feb 29-Mar 31
13/ 9	cesium	0.9	3.1	3.5	172	Apr 1-Apr 23
6/ 3	rubidium	7.2	21.0	15.3	164	Feb 29-Mar 31*
6/ 3	rubidium	5.3	13.4	5.8	117	Apr 1-Apr 23
9/ 6	rubidium	5.1	14.4	6.4	203	Feb 29-Mar 31*
9/ 6	rubidium	4.2	10.6	3.6	134	Apr 1-Apr 23
8/ 4	quartz	5.8	14.1	10.3	267	Feb 29-Mar 31
8/ 4	quartz	1.9	10.7	9.8	171	Apr 1-Apr 23

* eclipse season.