Precise Orbits and Clocks

An introduction to the SP3 file format used to store precise GNSS satellite orbit and clock data

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Precise Orbits and Clocks I

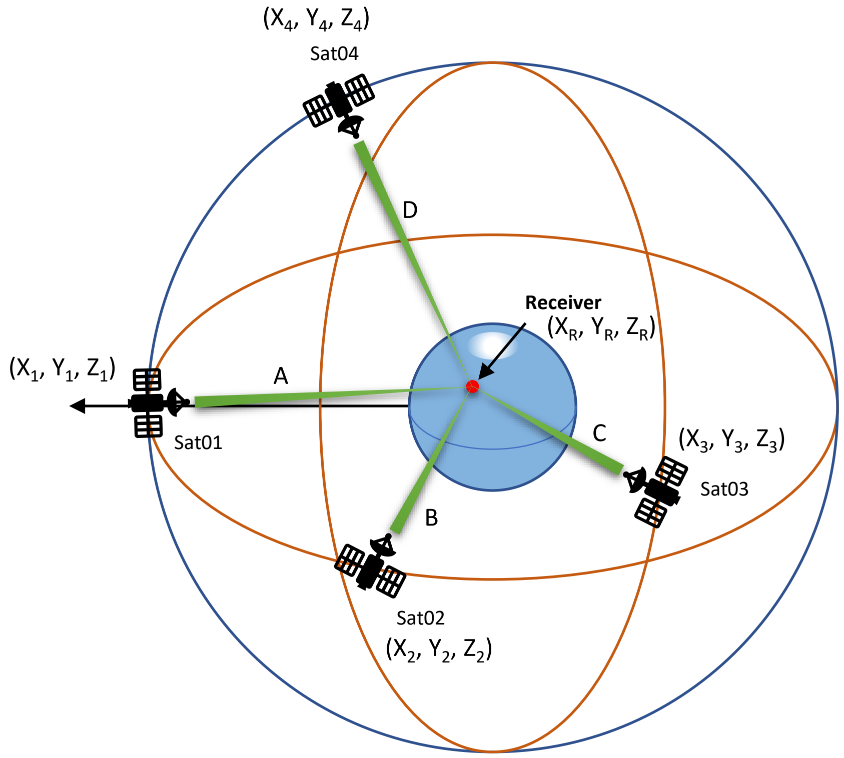
Working out where you are on the Earth using navigation satellites relies on two things:

- Knowing exactly where those satellites are, and
- Knowing exactly how far away you are from each satellite.

If you know those things you can use trigonometry to calculate where you are.

But the nature of global navigation satellite systems means that some errors or unknowns creep in which makes the calculated position less accurate than it could be.

For example, the satellite tells you its position but that position isn't quite right. Its onboard clock is a little out. Both of these things affect your receiver's ability to know how far you are from the satellite and thus reduces the accuracy of the calculated position.

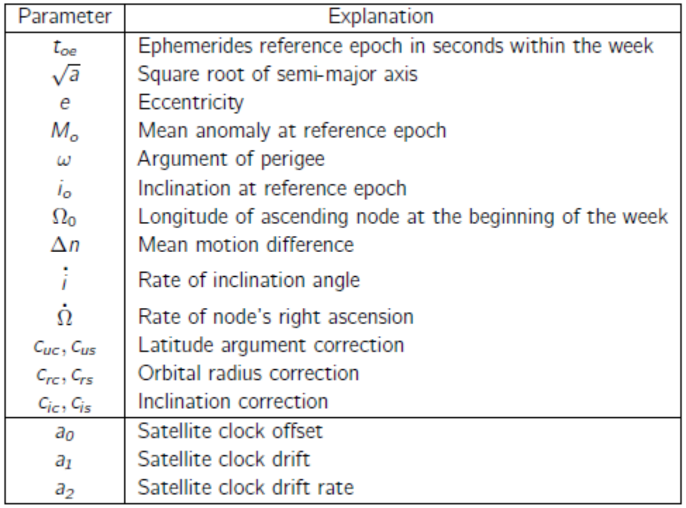


If you know A, B, C and D and all the X, Ys and Zs then you can calculate X_R, Y_R and Z_R.

Precise Orbits and Clocks II

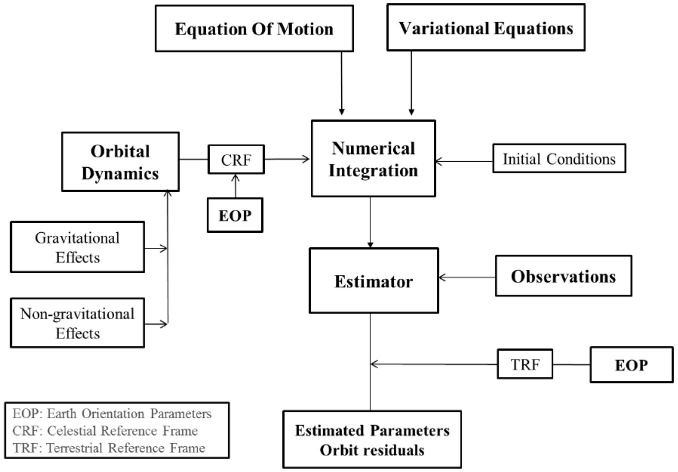
Satellites broadcast data about their orbit (ephemeris) on a regular basis, and this data is used by GNSS receivers to derive positions. The ephemeris data, while accurate, is not as accurate as it could be. The original GPS ephemeris had a precision of about a meter. The newer system Galileo broadcasts data which is three times more precise. As the technology and techniques develop, so will the precision of the satellite broadcast ephemeris data.

Table 3.8: GPS/Galileo/Beidou broadcast ephemeris and clock message parameters.



Parameter	Explanation
t_{oe}	Ephemerides reference epoch in seconds within the week
$\sqrt{a}$	Square root of semi-major axis
e	Eccentricity
M_o	Mean anomaly at reference epoch
ω	Argument of perigee
i_o	Inclination at reference epoch
Ω_0	Longitude of ascending node at the beginning of the week
Δn	Mean motion difference
$\dot{i}$	Rate of inclination angle
$\dot{\Omega}$	Rate of node's right ascension
c_{uc}, c_{us}	Latitude argument correction
c_{rc}, c_{rs}	Orbital radius correction
c_{ic}, c_{is}	Inclination correction
a_0	Satellite clock offset
a_1	Satellite clock drift
a_2	Satellite clock drift rate

A Precise Orbit Determination (POD) system



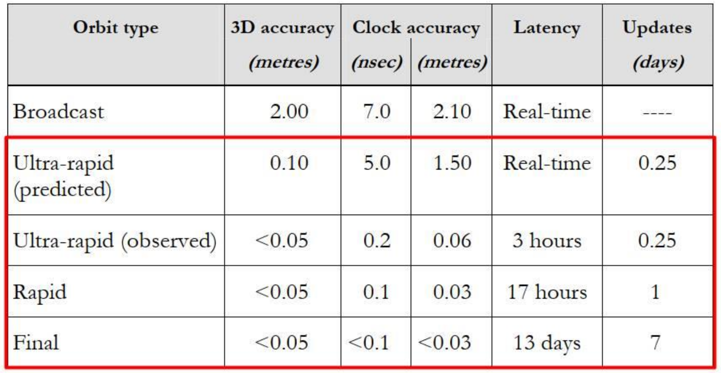
The clock and orbit data broadcast by the satellites is calculated within the satellite and periodically adjusted by ground control stations. At the same time ground based GNSS reference stations collect GNSS data (observables) and using sophisticated orbit correction models, are able to produce very accurate GNSS satellite orbit and clock data. Precise Point Positioning (PPP) applications, such as Ginan from Geoscience Australia, have their own Precise Orbit Determination (POD) components to do this type of work. These applications usually produce precise orbit and clock data in the SP3-d file format (and as a message in a real-time data stream).

Precise Orbits and Clocks III

Analysis products such as SP3 files, may be classified according to their latency – the length of time between the time of the last observations and the time the file is produced. The table to the right shows the versions of the orbit and clocks product, differentiated by latency, produced by the International GNSS Service (IGS).

The ultra-rapid product, useful for real-time and near real-time applications, is produced four times per day; the ultra-rapid product includes both observed and predicted satellite orbits. The rapid orbit combination is a daily solution available approximately 17 hours after the end of the previous UTC day. The final, most consistent and highest quality IGS solutions, consist of daily orbit files, generated on a weekly basis approximately 13 days after the end of the solution week.

IGS product type, accuracy and latency



Orbit type	3D accuracy	Clock accuracy		Latency	Updates
	(metres)	*(nsec)*	*(metres)*		*(days)*
Broadcast	2.00	7.0	2.10	Real-time	----
Ultra-rapid (predicted)	0.10	5.0	1.50	Real-time	0.25
Ultra-rapid (observed)	<0.05	0.2	0.06	3 hours	0.25
Rapid	<0.05	0.1	0.03	17 hours	1
Final	<0.05	<0.1	<0.03	13 days	7

A crucial role is played by the International GNSS Service (IGS) - up to eight IGS Analysis Centres (AC) contribute daily Ultra-rapid, Rapid and Final GPS orbit and clock solutions to form IGS analysis products. Properly weighted combinations of results from the ACs can produce products which are superior in precision, accuracy, stability, reliability, and robustness compared to the results of any individual AC.

Figure 1: Weighted orbit RMS of the IGS Rapid (*IGR*) products and AC Final orbit solutions during 1994-2009 with respect to the IGS Final orbit products.

- COD – Center for Orbit Determination
- EMR – Natural Resources Canada
- ESA – European Space Agency
- GFZ – GeoForschungsZentrum
- JPL – Jet Propulsion Laboratory
- MIT – Massachusetts Institute of Technology
- NGS – National Geodetic Survey
- SIO – Scripps Institute of Oceanography
- IGR – International GNSS Service Rapid products

From: A GUIDE TO USING INTERNATIONAL GNSS SERVICE (IGS) PRODUCTS,
Jan Kouba, Geodetic Survey Division, Natural Resources Canada

SP3-d file overview

Header block – time and configuration data, satellite identification

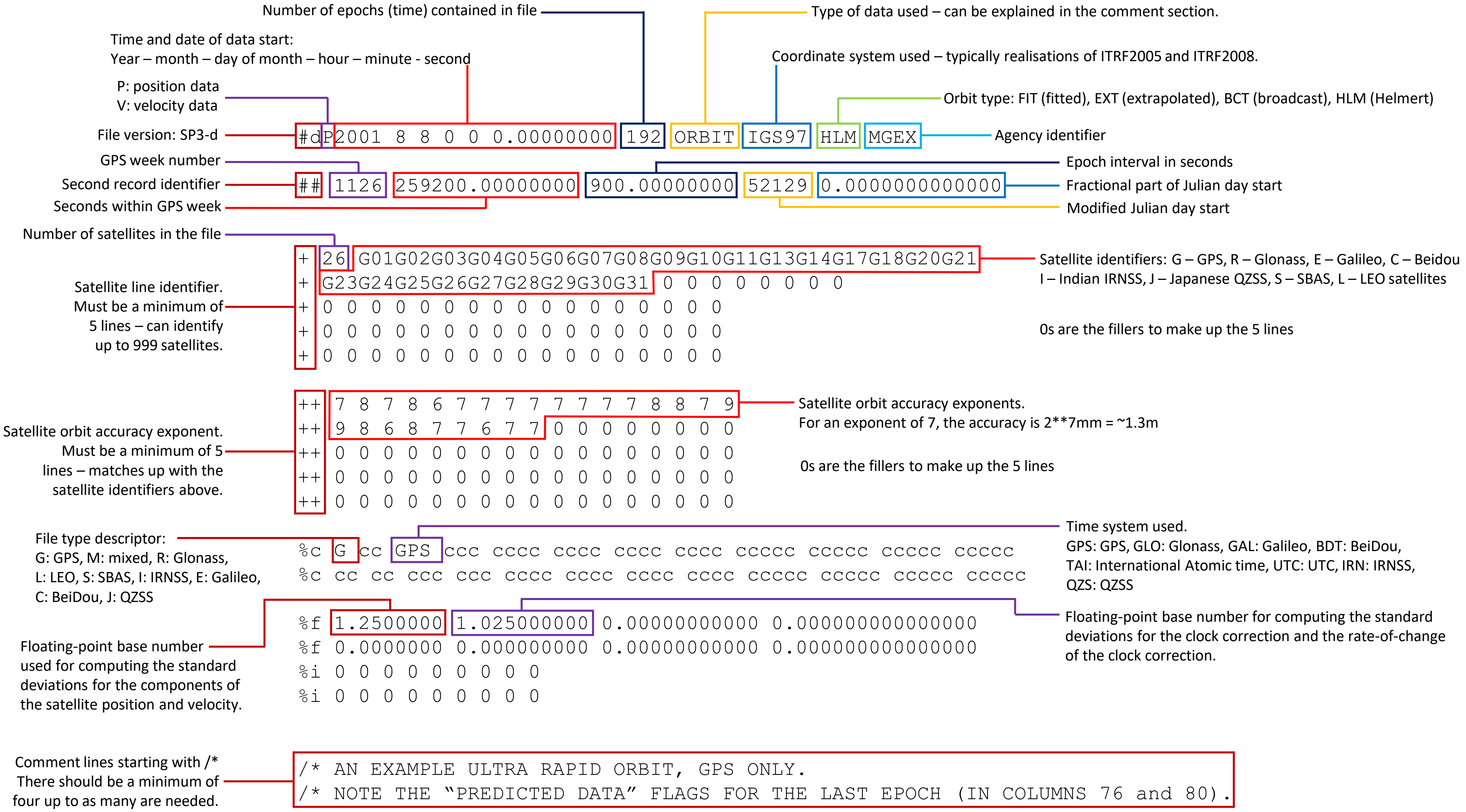
- Data type in file, date and time of file, coordinate system and publishing agency
- GPS week and time, epoch intervals
- Satellite identification
- Satellite orbit accuracy exponents.
- Area for other parameters.
- Area for comments on the file.

Data block – data on satellites organised by epoch (time)

- Items which may be present for each epoch.
  - Epoch date and time
  - P record for a specified satellite – X Y Z position coordinates in kilometres,, clock value in microseconds
  - V record for a specified satellite – X Y Z velocity in decimeters/second, rate of change of clock value in 10**-4 microseconds/second
  - EP record for a specified satellite – optional position and clock correlation record. Standard deviation of X Y Z position in mm, standard deviation of the clock correction in picoseconds.
  - EV record for a specified satellite – optional velocity and clock rate-of-change correlation record. Standard deviation of the X Y Z velocities in 10**-4 millimetres/second. Standard deviation of the clock correction rate-of-change in units of 10**-4 picoseconds/second.

SP3-d file example header block

Note: a real SP-d file does not have blank lines between lines. These have been added below to help fit in the explanatory notes.



```
#dP2001  8  8  0  0  0.00000000 192 ORBIT IGS97 HLM MGEX
## 1126 259200.00000000 900.00000000 52129 0.0000000000000

+  26 G01G02G03G04G05G06G07G08G09G10G11G13G14G17G18G20G21
+     G23G24G25G26G27G28G29G30G31  0  0  0  0  0  0  0  0
+     0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+     0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+     0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0

++    7  8  7  8  6  7  7  7  7  7  7  7  7  8  8  7  9
++    9  8  6  8  7  7  6  7  7  0  0  0  0  0  0  0  0
++    0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
++    0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
++    0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0

%c G  cc GPS ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc
%c cc cc ccc ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc

%f  1.2500000  1.025000000  0.00000000000  0.000000000000000
%f  0.0000000  0.000000000  0.00000000000  0.000000000000000
%i    0    0    0    0      0    0    0    0         0
%i    0    0    0    0      0    0    0    0         0

/* AN EXAMPLE ULTRA RAPID ORBIT, GPS ONLY.
/* NOTE THE "PREDICTED DATA" FLAGS FOR THE LAST EPOCH (IN COLUMNS 76 and 80).
```

Number of epochs (time) contained in file

Type of data used – can be explained in the comment section.

Time and date of data start:
Year – month – day of month – hour – minute - second

Coordinate system used – typically realisations of ITRF2005 and ITRF2008.

P: position data
V: velocity data

Orbit type: FIT (fitted), EXT (extrapolated), BCT (broadcast), HLM (Helmert)

File version: SP3-d

Agency identifier

GPS week number

Epoch interval in seconds

Second record identifier

Fractional part of Julian day start

Seconds within GPS week

Modified Julian day start

Number of satellites in the file

Satellite identifiers: G – GPS, R – Glonass, E – Galileo, C – Beidou
I – Indian IRNSS, J – Japanese QZSS, S – SBAS, L – LEO satellites

Satellite line identifier. Must be a minimum of 5 lines – can identify up to 999 satellites.

0s are the fillers to make up the 5 lines

Satellite orbit accuracy exponents.
For an exponent of 7, the accuracy is 2**7mm = ~1.3m

Satellite orbit accuracy exponent. Must be a minimum of 5 lines – matches up with the satellite identifiers above.

0s are the fillers to make up the 5 lines

File type descriptor:
G: GPS, M: mixed, R: Glonass,
L: LEO, S: SBAS, I: IRNSS, E: Galileo,
C: BeiDou, J: QZSS

Time system used.
GPS: GPS, GLO: Glonass, GAL: Galileo, BDT: BeiDou,
TAI: International Atomic time, UTC: UTC, IRN: IRNSS,
QZS: QZSS

Floating-point base number used for computing the standard deviations for the components of the satellite position and velocity.

Floating-point base number for computing the standard deviations for the clock correction and the rate-of-change of the clock correction.

Comment lines starting with /*
There should be a minimum of four up to as many are needed.

SP3-d file example - data

Epoch date time

```
*  2001  8  8  0  0  0.00000000
```

Position

Satellite ID

X value

Y value

Z value

Clock

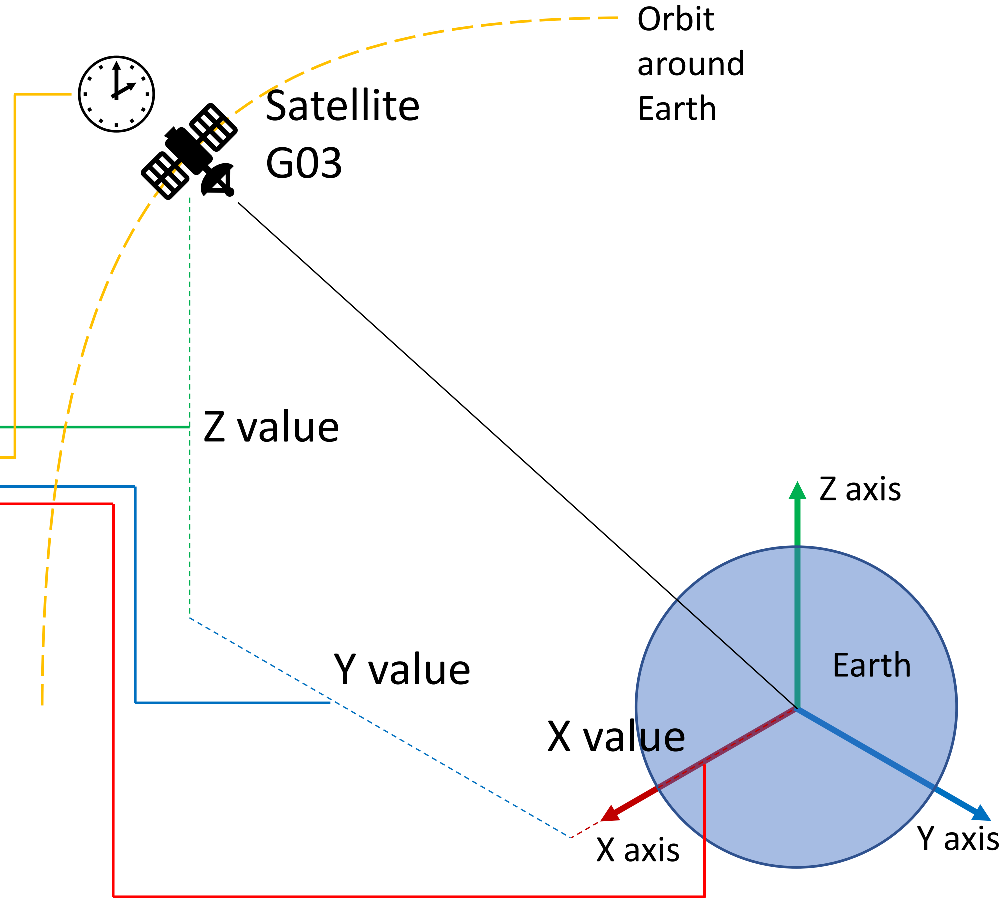
```
PG01 5783.206741 -18133.044484 -18510.756016 12.734450
PG02 -22412.401440 13712.162332 528.367722 425.364822

PG03 10114.112309 -17446.189044 16665.051308 189.049475


PG04 -24002.325710 4250.313148 -11163.577756 179.333612
PG05 -15087.153141 8034.886396 20331.626539 -390.251167
PG06 13855.140409 -11053.269706 19768.346019 289.556712
.
.
.
```

Data for another epoch

```
*  2001  8  9 23 45  0.00000000
PG01 4340.761149 -17469.395805 -19521.652181 13.021579
PG02 -22187.015530 13877.264416 2583.141886 425.527461
PG03 9785.535610 -18824.396329 15333.698561 189.465625
PG04 -24642.374460 4816.578416 -9365.337848 180.261632
PG05 -13667.233808 8977.038381 20922.734874 -390.371011
PG06 13696.828033 -12657.020030 18869.219517 288.240920
.
.
.
EOF
```



Note: a real SP-d file does not have blank lines between lines. These have been added below to help fit in the explanatory notes.
The V, EP and EV record types are not shown in this example.

SP3-d file example – real file

```
#dP2017  3 29  0  0  0.00000000      96 ORBIT IGS
14 HLM  IGS## 1942 259200.00000000   900.00000000 57841 0.0000000000000
+   32   G01G02G03G04G05G06G07G08G09G10G11G12G13G14G15G16G17
+        G18G19G20G21G22G23G24G25G26G27G28G29G30G31G32  0  0
+          0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+          0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
+          0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
++         1  2  2  0  2  2  2  2  2  2  2  3  2  2  2  2  2
++         2  2  2  2  2  2  2  2  2  1  2  2  2  2  2  0  0
++         0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
++         0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
++         0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
%c G  cc GPS ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc
%c cc cc ccc ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc
%f  1.2500000  1.025000000  0.00000000000  0.000000000000000
%f  0.0000000  0.000000000  0.00000000000  0.000000000000000
%i    0    0    0    0      0      0      0      0         0
%i    0    0    0    0      0      0      0      0         0
/* FINAL ORBIT COMBINATION FROM WEIGHTED AVERAGE OF:
/* cod emr esa gfz grg jpl mit ngs sio
/* REFERENCED TO IGS TIME (IGST) AND TO WEIGHTED MEAN POLE:
/* PCV:IGS14_1930 OL/AL:FES2004  NONE     Y  ORB:CMB CLK:CMB
•  2017  3 29  0  0  0.00000000
•  PG01  13468.180209 -15714.948137  16388.180018     52.267516  7  4  9 120
•  PG02 -14227.390968  -8017.994334 -20506.857548    450.089308  9 11  7 128
•  PG03  22329.595919 -13372.180140  -5237.243105   -105.963214  8  7  8 105
•  PG04  11936.190982  10697.761976 -21454.649717 999999.999999
•  PG05 -23125.831238   -302.341470 -13321.736943    -53.443172 10  6  8 100
•  PG06  -7413.463000 -21059.824533 -14352.466041    330.665316  8  9  7  92
•  PG07   7221.007672 -24775.126497  -5078.259847    368.285870  9  8 11  86
•  PG08  20725.303414   1016.712981  16687.809065    -54.389560  6  7  8 114
•  PG09   1990.137990 -16694.765350 -20586.132180    331.550108  7  7  5 102
•  PG10   5046.792791  14399.425428  21761.443567    -86.596028  4  4  6 108
•  PG11  13521.926322 -10290.651944  19860.647962   -677.801326  5  6  7 113
```

SP File Format – using

An SP3 file contains the precise position and clock of a satellite at a certain point in time (epoch).

No position or clock is absolutely correct and the file contains data which gives the user an indication of the accuracy of the data.

This in part is driven by the type of file – final, rapid or ultra-rapid. The final files are the most accurate, but the ultra-rapid (and stream data) are obviously most useful for near real-time work.

Positions are given at certain points in time. As a user, if you need to determine a position at a time between two given points, you will have to use an orbital model and interpolate between the two known points to derive a position at the time required. Orbits are predictable so this is a very practical and useful thing to do.

Clocks, due to their noise characteristics are more problematic. The closer the two points are in time the better.

SP File Format – more information

SP stands for Standard Product and the first file specification SP1 was first released in 1985 by Benjamin Remondi working for the US National Geodetic Survey. At the time the only satellite based navigation constellation in operation was the US Global Positioning System (GPS) and SP1 was focussed on being a means of distributing precise GPS orbit data.

Since 1985 the file specification has undergone many revisions to enhance the data it can contain. In 2016 the SP3-d specification was released. This format supports:

- Satellite identification numbers from all the global navigation satellite systems (GNSS) and satellite based augmentation systems (SBAS) currently in operation, and up to 999 individual satellites,
- Precise orbit details but also clock corrections,
- Clock event and orbit manoeuvre flags,
- More generous space for comments.

For more information on the SP3-d format please refer to [1]. For more information on the history of the SP format please refer to [1] and [2].

[1] The Extended Standard Product 3 Orbit Format (SP3-d), 21 February 2016, Steve Hilla, National Geodetic Survey, National Ocean Service, NOAA, Silver Spring, MD 20910, USA.

[2] NOAA Technical Report NOS 133 NGS 46, Extending the National Geodetic Survey Standard GPS Orbit Formats, Benjamin W. Remondi, Rockville, MD, November 1989

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