7. External Data Sources and Data Transfer

7.1 Transfer to RINEX

7.1.1 RINEX: The Receiver-Independent Exchange Format

All GPS data processing programs contain an explicit definition of the GPS observables that are to be used with that program. If these programs are to process data from different receivers they must first convert the raw receiver information to these local definitions and formats. In order to facilitate this task an exchange format has been designed that allows the conversion of any raw receiver data not only into this format but also into an explicit definition of the observables.

The Astronomical Institute of the University of Berne developed a first version of such a format to be used for the data exchange and processing of the EUREF-89 GPS campaign, a campaign observed in May 1989 involving four different receiver types and nearly one hundred stations in most countries of Western Europe. The format started from a format developed and used by the US National Geodetic Survey for the exchange of GPS data collected in the CIGNET GPS network, the first global network of permanent GPS receivers used for civil geodetic purposes. The new format, named RINEX (Receiver-Independent Exchange Format) was presented to the geodetic community at the Fifth International Geodetic Symposium in Satellite Positioning in Las Cruces, New Mexico in March 1989 where it was accepted as the format to be recommended for geodetic GPS data exchange. A second version (RINEX Version 2) was discussed and accepted at the Second International Symposium on Precise Positioning with the Global Positioning System in Ottawa, Canada in September 1990.

The format descriptions have been published in the *CSTG GPS Bulletins May/June 1989 and September/October 1990*. The most recent description can be found on various WWW and ftp servers, e.g. on

`ftp://igscb.jpl.nasa.gov/igscb/data/format/rinex2.txt`

or on our anonymous ftp account:

```
Internet:  ubeclu.unibe.ch
Directory: cd aiub$ftp
           cd rinex
File:      rinex2.txt
```

The basic observables to be used in the RINEX format are:

- The epochs of observations defined as the time of the received signals expressed in the receiver time frame. The epochs are identical for all satellites (i.e. simultaneous observations with respect to receiver time).
- Carrier phase observations (integrated negative beat frequency between the received carrier of the satellite signal and the receiver-generated reference frequency). The sign is the same as for the pseudorange, i.e. decreasing phase if the satellite approaches the receiver.
- Pseudorange observations, i.e. the difference between the time of reception of a satellite code signal, expressed in receiver time, and the time of emission of the same signal, expressed in satellite time.

The three quantities are based on the same oscillator, i.e. that any offsets and drifts of the oscillator directly show in the basic observables.

Other observables have been defined for the direct doppler frequency observations and for meteorological measurements.

Currently there are three different file types defined:

RINEX Observation Files

A RINEX Observation File contains data collected by one receiver only. Usually a file also contains only data from one station and one session although there are possibilities to store e.g. data collected by a roving receiver during kinematic or pseudokinematic surveys.

The file consists of a header section with all auxiliary information about the station and receiver necessary for the post-processing of the data and the data section with the basic observables.

The recommended file naming is as follows:

ssssdddf.yy`O`

ssss is a four-character station code, *ddd* and *yy* are the day of the year and the two-digit year of the first observation epoch in the file, *f* is a file sequence number (to separate files collected during the same day), and `O` is the label for observation files.

```
     2              OBSERVATION DATA    G (GPS)             RINEX VERSION / TYPE
TRRINEXO V2.8.1 LH  L+T                 30-AUG-96 00:36     PGM / RUN BY / DATE
Zimmerwald LT88                                             COMMENT
BIT 2 OF LLI (+4) FLAGS DATA COLLECTED UNDER "AS" CONDITION COMMENT
ZIMM                                                        MARKER NAME
14001M004                                                   MARKER NUMBER
LOGST/COMPAQ        L+T                                     OBSERVER / AGENCY
2691                TRIMBLE 4000SSE     5.68                REC # / TYPE / VERS
67905               4000ST L1/L2 GEOD                       ANT # / TYPE
  4331297.3360   567555.5574  4633133.6772                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
     1     1                                                WAVELENGTH FACT L1/2
     5    C1    L1    L2    P2    P1                        # / TYPES OF OBSERV
    30                                                      INTERVAL
  1996     8    29     0     0   30.000000                  TIME OF FIRST OBS
                                                            END OF HEADER
 96  8 29  0  0 30.0000000  0  9 04 20 05 26 23 07 01 09 21
  24841044.211      -46870.514 5
                  -2797653.294 5  -2180114.401 2  22410465.238    22410465.203
  20586648.008   -12789115.369 8  -9884138.00946  20586645.5474
  24202218.266    19847070.932 5  15529019.72141  24202217.5044
  24943196.180     3447366.671 2   1718907.78841  24943197.1764
  23526132.711     5295013.883 6   4192590.48142  23526131.3874
  23543864.500    -4688636.158 6  -3575508.90842  23543863.4924
  20507534.195    -8368858.658 8  -6449216.43547  20507532.9534
  24369300.672      486541.758 4    285006.12841  24369299.9104
 96  8 29  0  1  0.0000000  0  9 04 20 05 26 23 07 01 09 21
  24833459.859      -86724.125 5    -20677.15741  24833458.5944
                  -2852353.594 5  -2222740.702 2  22400057.922    22400058.938
  20587075.055   -12786871.980 8  -9882389.90746  20587072.8164
  24228348.266    19984388.207 5  15636020.22941  24228346.0514
  24964712.000     3560428.704 4
  23546780.625     5403517.837 6   4277139.02641  23546778.0474
  23534026.203    -4740341.622 6  -3615798.87542  23534025.0904
  20517038.250    -8318916.570 8  -6410300.53247  20517036.5744
  24385113.508      569640.718 5    349758.59041  24385113.8484
                                          .
                                          .
                                          .
```

Figure 7.1: RINEX Observation File

RINEX Navigation Message Files

The RINEX Navigation Message Files contain the broadcast messages for all satellites collected during the respective sessions.

The recommended file naming is as follows:

ssssdddf.yy`N`

with `N` as the label for the Navigation Message Files.

Usually there is no need to exchange all the navigation messages collected at all the stations of a network in separate files. One comprehensive file containing non-redundantly every possible message might be preferable. In this case *ssss* could be a code for the agency producing this file.

```
     2              NAVIGATION DATA                         RINEX VERSION / TYPE
TRRINEXN V2.10 LH   L+T / AIUB          30-AUG-96 00:40     PGM / RUN BY / DATE
Zimmerwald LT88                                             COMMENT
    0.6519E-08  0.1490E-07 -0.5960E-07 -0.1192E-06          ION ALPHA
    0.7782E+05  0.3277E+05 -0.6554E+05 -0.1966E+06          ION BETA
   -0.558793544769E-08-0.799360577730E-14   503808      868 DELTA-UTC: A0,A1,T,W
    11                                                      LEAP SECONDS
                                                            END OF HEADER
20 96  8 29  0  0  0.0 0.195149797946E-03 0.247837306233E-10 0.000000000000E+00
    0.184000000000E+03-0.774062500000E+02 0.521307428833E-08-0.837128051183E+00
   -0.409409403801E-05 0.510782771744E-02 0.670179724693E-05 0.515279819489E+04
    0.345600000000E+06-0.409781932831E-07-0.860457352085E+00 0.782310962677E-07
    0.951221289659E+00 0.242906250000E+03 0.130404363687E+01-0.858500045687E-08
   -0.788604277105E-09 0.100000000000E+01 0.868000000000E+03 0.100000000000E+01
    0.600000000000E+01 0.100000000000E+01 0.372529029846E-08 0.184000000000E+03
    0.345570000000E+06 0.000000000000E+00 0.000000000000E+00 0.000000000000E+00
 7 96  8 28 22 51 44.0 0.726384576410E-03 0.682121026330E-12 0.000000000000E+00
    0.184000000000E+03 0.560312500000E+02 0.392730644522E-08-0.285627348369E+01
    0.295229256153E-05 0.836740608793E-02 0.137649476528E-04 0.515364046478E+04
    0.341504000000E+06-0.186264514923E-07 0.200086231538E+00-0.968575477600E-07
    0.964051037327E+00 0.116781250000E+03-0.241671120817E+01-0.757567270003E-08
    0.635740766869E-10 0.100000000000E+01 0.868000000000E+03 0.000000000000E+00
    0.320000000000E+02 0.000000000000E+00 0.139698386192E-08 0.184000000000E+03
    0.345570000000E+06 0.000000000000E+00 0.000000000000E+00 0.000000000000E+00
 1 96  8 29  0  0  0.0 0.829342752695E-06 0.113686837722E-11 0.000000000000E+00
    0.129000000000E+03-0.122812500000E+02 0.442411285349E-08 0.304274422694E+01
   -0.545755028725E-06 0.355291063897E-02 0.141207128763E-04 0.515363731956E+04
    0.345600000000E+06 0.119209289551E-06-0.290897687470E+01-0.186264514923E-08
    0.954830250044E+00 0.102656250000E+03-0.148647045470E+01-0.786461330700E-08
    0.286440502825E-09 0.100000000000E+01 0.868000000000E+03 0.000000000000E+00
    0.320000000000E+02 0.000000000000E+00 0.139698386192E-08 0.385000000000E+03
    0.345570000000E+06 0.000000000000E+00 0.000000000000E+00 0.000000000000E+00
                                         .
                                         .
                                         .
```

Figure 7.2: RINEX Navigation Message File

RINEX Meteorological Data Files

The RINEX Meteorological Data Files are used for the exchange of weather data collected at GPS stations.

The recommended file naming is as follows:

ssssdddf.yy`M`

with `M` as the label for the Meteorological Data Files.

```
     2              METEOROLOGICAL DATA                     RINEX VERSION / TYPE
QLRINEXO V1.0.0 VM  AIUB                06-JUN-96 14:50     PGM / RUN BY / DATE
CDP SYSNUM:    34   CDP OCCNUM:    02   SYS CONFIG:     2   COMMENT
7839 GRAZ                                                   MARKER NAME
     3    PR    TD    HR                                    # / TYPES OF OBSERV
                                                            END OF HEADER
 96  5 31  8 34 28  964.7   20.1   54.0
 96  5 31  8 38 15  964.7   20.1   54.0
 96  5 31  8 42 34  964.7   20.1   54.0
 96  5 31  8 46 25  964.7   20.1   54.0
 96  5 31  9 18 49  964.7   20.1   54.0
 96  5 31  9 23  7  964.7   20.1   54.0
 96  5 31  9 49 21  964.7   20.1   54.0
 96  5 31  9 52 50  964.7   20.1   54.0
 96  5 31  9 57 48  964.7   20.1   54.0
 96  5 31 10  2 14  964.7   20.1   54.0
 96  5 31 10  7 42  964.7   20.1   54.0
 96  5 31 10 12 42  964.7   20.1   54.0
 96  5 31 10 17 33  964.7   20.1   54.0
 96  5 31 10 22 34  964.7   20.1   54.0
 96  5 31 10 27 41  964.7   20.1   54.0
 96  5 31 10 32 18  964.7   20.1   54.0
 96  5 31 10 35 50  964.7   20.1   54.0
 96  5 31 10 52 58  964.7   20.1   54.0
 96  5 31 10 57 54  964.7   20.1   54.0
 96  5 31 11  2 41  964.7   20.1   54.0
 96  5 31 11  7  8  964.7   20.1   54.0
                                          .
                                          .
                                          .
```

Figure 7.3: RINEX Meteorological Data File

7.1.2 Data Conversion to RINEX

As the manufacturer knows the properties and internals of the receiver and its data best, the ideal case is where the manufacturer directly provides data in RINEX format or at least provides software to do the conversion from the raw receiver data to RINEX.

Ashtech, Leica, and Trimble all include into their own post-processing software programs to generate RINEX files from the raw data.

We recommend to use this original conversion software if possible.

The Bernese GPS Software also contains conversion programs for various receiver types:

Receiver Types	Converter Programs
Ashtech L12/P12/Z12	ASRINEXO, ASRINEXN
Minimac	MCRINEXO, MCRINEXN
Rogue and Turborogue	RGRINEXO, RGRINEXN
Trimble 4000 SST/SSE/SSI	TRRINEXO, TRRINEXN
WM-101, WM-102	WMRINEXO, WMRINEXN

Table 7.1: Bernese RINEX Converters

In addition to these programs a few auxiliary programs are made available for RINEX file manipulation and RINEX met file creation:

Action	Converter Programs
File concatenation	CCRINEXO, CCRINEXN
Met file creation	RXMETEO
File splitting	RNXSPLIT
Display File contents	RNXGRA

Table 7.2: Auxiliary Programs

With the exception of the WM and Minimac converters all programs run on all computer systems supported by the Bernese GPS Software. The former ones are only available under DOS.

The conversion programs are included in the menu system in Panel 2.5. The help panels should give enough information about the options to be used. Additional information can also be found in the `PCRINEX`-Directory on our anonymous ftp account (see below) in the text file `PCRINEX.TXT`.

As there may always be changes in the raw data format coming with new receivers the distributed converter programs might not be the versions to be used. As long as we support the creation of RINEX files for the above mentioned receiver types with our own converters, the latest versions (at least the executables for DOS) can always be downloaded from our anonymous ftp account:

```
Internet:  ubeclu.unibe.ch
Directory: cd aiub$ftp
           cd pcrinex
Files:     386rnx1.zip
           386rnx2.zip
```

Please contact AIUB for updated source for UNIX and VMS systems.

7.2 Transfer RINEX ⟷ Bernese

The RINEX format is well suited for data transfer. RINEX is very flexible, and because it is an ASCII format, the transfer between different operating systems is simple. However, the processing software has to work extensively with observation files. The input/output operations are much faster if binary files are used. Therefore the Bernese GPS Software transfers all the RINEX observation files and navigation messages into the Bernese binary format. If RINEX meteo files are to be used, they are translated, too. In this case, however, the Bernese file is an ASCII file as well.

We refer to Chapter 23 for the description of files used by the Bernese GPS Software. If the RINEX file contains both, phase and code, observations of one station, the following four Bernese observation files are created for each RINEX file:

`*.PZH` ... phase zero-difference header file (contains information about the station, receiver, antenna, ambiguities etc.),

`*.PZO` ... phase zero-difference observation file (contains phase observations),
`*.CZH` ... code zero-difference header file (contains similar information as the phase zero-difference file, but no ambiguities),
`*.CZO` ... code zero-difference observation file (contains code observations).

The navigation messages in RINEX files are transferred into Bernese broadcast orbit files (usually with the extension `.BRD`). The RINEX files containing meteorological data are translated into Bernese meteo files (extension `.MET`).

Transfer RINEX ⟶ Bernese

There are three programs in the transfer part of the Bernese GPS Software translating RINEX data into the Bernese format. All programs are accessible through Menu 2.7.

RXOBV3 (Menu 2.7.1) transforms RINEX observation data into Bernese code/phase header/observation files. The format of the Bernese files did not change since Version 3.4. The program may process a list of RINEX observation files. The user may specify so-called translation tables to modify information coming from RINEX files. There are three translation tables which may be used. Examples for all three tables may be found in Chapter 4.

The station name translation table may be used to make sure that you end up with a unique set of station names in the Bernese observation files. It has the default extension `.STN` and is located in the campaign-specific station directory `STA`.

The receiver/antenna name translation table may be used to define a unique set of receiver and antenna names. The file containing this table is located in the `X:[GEN]` (`$X/GEN` on Unix, `X:\GEN` on DOS) directory and has the default extension `.TRN`.

The antenna height translation table may be important if the antenna heights in the RINEX files are wrong or if they have been measured with respect to a non-standard reference point. The translation table has the default extension `.HTR` and it is located in the campaign-specific station directory `STA`.

For more details concerning the options of program RXOBV3 we refer to the corresponding help panels. RXOBV3 does not accept more than one station in each RINEX file. If data stemming from more stations are stored in one RINEX file, it is necessary to split up the RINEX file using program RNXSPLIT (see Section 7.1.2).

RXNBV3 (Menu 2.7.2) transforms the RINEX navigation messages into Bernese broadcast files. The program has no options. It can process a list of RINEX navigation files.

RXMBV3 (Menu 2.7.3) transforms the RINEX meteo files into Bernese meteo files. RINEX provides one meteo file per site and session, in the Bernese format one meteo file per site (in one run of the program GPSEST only one meteo file per site may be specified) is required. Therefore the program RXMBV3 may concatenate RINEX meteo files from different sessions into one (site-specific) Bernese meteo file. Optionally a station name translation table may be used.

There are two more programs accessible through Menu 2.7. RNXGRA (Menu 2.7.4) creates a simple graphic of the observations available in the RINEX file(s) selected. RNXCYC (Menu 2.7.5) could be used for a pre-processing step on the RINEX level. This program is described in Chapter 10.

Transfer Bernese ⟶ Rinex

The program BV3RXO (Menu 2.6.1) transforms Bernese code/phase header/observation files into RINEX format observation files. More than one Bernese file may be written into one RINEX observation file. Be aware of the fact that only single difference files are cleaned in the Bernese processing procedure and that RINEX files generated from Bernese *zero-difference* files are therefore not clean. Program BV3RXO makes use of a so-called receiver information file to supply additional information needed to create the RINEX headers (see Panel 0.3.1 and Chapter 23).

The program BV3RXN transforms one or more Bernese broadcast file(s) into RINEX navigation message file(s). Normally, for each Bernese broadcast input file one RINEX output file will be created, but it is also possible to specify the same output file for several Bernese input files. All messages will then be written into the same RINEX navigation message file.

7.3 SINEX Format

7.3.1 SINEX Definition

At the 1994 IGS Workshop on the *Densification of the IERS Terrestrial Reference Frame through Regional GPS Networks* (JPL, Pasadena, Dec. 1994) it was decided to start an IGS pilot project to prove the concept for a *distributed processing* of GPS data (see e.g. Section 18.4).
For that purpose it was necessary to define a data (resp. solution) exchange format, the Software INdependent EXchange format (SINEX). This format should contain all important information necessary to combine coordinates, velocities, and Earth Orientation Parameter (EOP) estimates. In Section 23.8.12 we give more information concerning the contents of SINEX files.

7.3.2 Bernese NEQ File ⟶ SINEX

SINEX files contain a subset of the information available in the Bernese normal equation files (see Section 23.8.8). The conversion Bernese NEQ ⟶ SINEX is generated by the combination program ADDNEQ, which allows to store normal equation files as well as SINEX files.

The SINEX files may contain additional information such as the 3-character identification of the agency, the identification of the data source, as well as information concerning the blocks "`FILE/REFERENCE`", "`FILE/COMMENT`", and "`INPUT/ACKNOWLEDGMENTS`". A general file, described in detail in Section 23.4.9, makes it possible to include this information into the SINEX file automatically.

The information, which became important recently (July 1996), is the elevation-dependent antenna phase center model used for the processing (see Section 23.4.5). In the present Version 4.0 the characters "`-----`" denoting items that are not specified are written into the SINEX file. If you use e.g. the recommended model `IGS_01` [*Rothacher*, 1996], you have to "hard-wire" this name in the source code of the subroutine `SINSAV`.

Writing Earth rotation parameters into the SINEX file is not supported by ADDNEQ, Version 4.0 .

A remark also concerning the station names used in the SINEX file. Let us assume that the station names used in the processing using Bernese consists of the 4-character codes of a site and the associated domes number (e.g. WETT 14201M009). In the SINEX format a site is characterized by the

4-character code and a PT flag (A-Z), indicating the occupation. We interpret the station names in a way that all stations with the same first 4 characters belong to the same site. It may cause troubles, if you use a different naming convention.

7.3.3 SINEX ⟶ Bernese NEQ File

ADDNEQ needs normal equations in the Bernese normal equation (.NEQ) format (see Section 23.8.8) as input. We developed the program SNXNEQ to allowing the conversion of SINEX files into Bernese NEQ files. Furthermore, SNXNEQ is able to generate Bernese coordinate (.CRD), velocity (.VEL), and variance-covariance (.COV) files. With these options you may "import" and process results obtained from other analysis centers using different processing tools.

The program may also be used to estimate approximate values of normal equation rescaling factors to ensure that in a combined solution all contributing solutions get a reasonable correct weight. The determination of proper rescaling values is essential, if you combine results obtained from different software packages.
As reference (rescaling factor 1.0) we use the SINEX file which is selected first in the F-file (more details are given below). For common sites (specified in the N-file with the keyword COVREF) we derive rescaling factors from the main diagonals of the associated normal equations (computed from the given covariance information). These rescaling factors may be stored in a .WGT file (keyword COVCOMO in the N-file). This file may then be used together with the generated normal equation files as input for ADDNEQ. More information is given in Chapter 18 and Section 23.8.13.

The program SNXNEQ is not yet supported by the menu system. Please use the command RUNGPS SNXNEQ (see Section 3.8) to prepare and start the program. Below, we give some important information concerning the input files.

N-File

```
SNXNEQ: INTERNAL AND EXTERNAL FILE NAMES                 24-AUG-96 16:18
------------------------------------------------------------------------
INTERNAL  EXTERNAL NAME                      DESCRIPTION
*******   ********************************

CONST     X:[GEN]CONST.                      GENERAL CONSTANTS
INPUT     U:[INP]SNXNEQI.INP                 INPUT OPTIONS
AUXFIL    U:[WORK]SNXNEQ.SCR                 AUXILIARY FILE
DATUM     X:[GEN]DATUM.                      GEODETIC DATUM
SNXFIL    U:[INP]SNXNEQF.INP                 SINEX INPUT FILES AND OUTPUT FILES
SYSOUT    K:[IGSA.OUT]SNXNEQ.L00             JOB OUTPUT
SYSERR    U:[WORK]ERROR.MSG                  ERROR MESSAGES
COORD     K:[IGSA.STA]ITRF94.CRD             APRIORI COORDINATE FILE
VELAPR                                       APRIORI VELOCITY FILE
NUMCNV    K:[IGSA.STA]ITRF94.CRD             COORDINATE FILE FOR STATION NUMBER
COVREF    K:[IGSA.STA]COMMON.CRD             REFERENCE STATIONS FOR COVARIANCES
COVCOMO   K:[IGSA.OUT]TEST.WGT               COVARIANCE COMPONENTS OUTPUT
```

Figure 7.4: N-File of Program SNXNEQ - on a VMS platform

The input files `CONST`, `INPUT`, `AUXFIL`, `DATUM`, `SNXFIL`, `SYSOUT`, and `SYSERR` are general files and need no special explanations.

`COORD` The specified coordinate file is used as master file to create coordinate files (specified in the F-file).

`VELAPR` The specified velocity file is used as master file to create velocity files (specified in the F-file).

`NUMCNV` SINEX files contain no station numbers. If station names given in the SINEX files are identical with the station names given in this coordinate file, the corresponding station number is written to the output coordinate files, velocity files, and normal equation files (specified in the F-file).

`COVREF` Coordinate file defining the common sites which are to be used to derive approximate rescaling factors. If you do not specify a file *all* sites of the SINEX files are used for the computation.

`COVCOMO` A `.WGT` output file containing the computed rescaling factors.

F-File

You have to enter the name of one or more than one SINEX file in the first column of the file. In the other columns you may specify the output files: `.NEQ` files, `.COV` files, `.CRD` files, and `.VEL` files.

I-File

Please do **not** change the default options (all settings to `NO (0)`).
We tested the conversion program SNXNEQ using the SINEX distributions of the global IGS Analysis Centers, the Global Network Associated Analysis Centers, and some Regional Network Associated Analysis Centers (SINEX files generated by at least 8-10 different SINEX "creators"). Due to the fact that not all agencies switched from the older 0.05 version to the new 1.00 version of the SINEX format it may happen, that our input routine `GETSIN` has problems with some "very new" SINEX files. We are prepared to assist you in the case of difficulties.

7.4 External Data Sources

7.4.1 CODE Products

The Center for Orbit Determination in Europe (CODE) is one of at present seven IGS Analysis Centers. CODE is a joint venture of the Astronomical Institute of the University of Berne with the Swiss Federal Office of Topography (L+T), the German Institute for Applied Geodesy (IfAG), and the French National Geographical Institute (IGN). CODE is located at the AIUB in Berne. The CODE IGS products are made available on the AIUB anonymous ftp account. Apart from these IGS products several other files that are specific to the Bernese GPS Software may be downloaded. This section describes how to use anonymous ftp to obtain the CODE and Bernese products.

In this section we use the following symbols:

symbol	meaning	example
wwww	gpsweek	0860
d	day of week	0:Sunday, 1:Monday ... 6:Saturday
yyyy	4 digit year	1996
yy	2 digit year	96
ddd	day of year	182

To access the anonymous ftp, which is located in Bern, use:

ftp	**ubeclu.unibe.ch** -or- **130.92.6.11**
login	**anonymous**
password	*your full e-mail address*
products	**cd aiub$ftp** to get to the AIUB anonymous ftp

After entering the anonymous ftp area in this way you will see several subdirectories. Our products are given in two main directory trees according to the following schematic.

```
BSWUSER --- ATM       CODE --- 1992
        |-- DATPAN         |-- 1993
        |-- GEN            |-- 1994
        |-- ORB            |-- 1995
        |-- OUT
        |-- STA
```

BSWUSER contains files specific to the Bernese GPS Software. These can either be general Bernese files or IGS products in a format specific to the Bernese software. Examples of general files, in the Bernese format of course, are the IERS pole files, the antenna phase center file, and the satellite information files. IGS products in the Bernese file format are for instance daily coordinate, troposphere, pole, and orbit estimates.

ATM contains our global 6-hourly tropospheric zenith delay estimates based on our global IGS analysis.

GEN contains general Bernese software files. Here the official IERS pole files (C04 and Bulletin A (rapid)) in the Bernese format, the "SATELLIT" and "SAT_yyyy.CRX" (satcrux) files and different antenna phase center files may be found.

OUT contains our daily ERP estimates, based on our global IGS analysis, in the Bernese pole format.

STA contains daily coordinate estimates of our global IGS analysis and of a separate European analysis. Also monthly ITRF coordinate files may be found here and the Bernese translation tables for the antenna heights and the station names of the IGS sites.

CODE contains our official IGS products. The products of the current year may be found in this main directory, those of previous years are found in subdirectories named after the year. Some of the products in the yearly directories have been compressed to save disk space. A summary of the IGS products available on our anonymous ftp is given in Table 7.3. The products include orbits, ERPs, satellite clocks, and global ionosphere models. Note that our precise orbit files should always be used together with the corresponding pole files!

Daily Products	
CODwwwwd.EP1	CODE 1-day orbits, available with a 3-day delay
CODwwwwd.ER1	CODE 1-day ERPs belonging to the 1-day orbits
CODwwwwd.ERH_R	CODE rapid orbits, available with a 16-hour delay
CODwwwwd.ERP_R	CODE rapid ERPs belonging to the rapid orbits
CODwwwwd.ION_R	CODE rapid global ionosphere model, Bernese format
CODwwwwd.EPH_P	CODE 24-hour orbit predictions
CODwwwwd.ERH_P2	CODE 48-hour orbit predictions
CODwwwwd.ERP_P	CODE predicted ERPs belonging to the predicted orbits
CODwwwwd.ERP_P2	CODE predicted ERPs belonging to the predicted orbits
Weekly Products	
CODwwwwd.EPH	CODE final orbits, our official orbit product!
CODwwwwd.ERP	CODE final ERPs belonging to the final orbits
CODwwww7.SUM	CODE weekly summary file
CODwwww7.SNX	CODE weekly SINEX file
CODwwwwd.ION	CODE daily global ionosphere model, Bernese format
CODwwwwd.CLK	CODE satellite clock estimates (5 min. sampl.), Bernese format
B1_yyddd.CLK	Broadcast satellite clock information, Bernese format

Table 7.3: CODE Products Available Through Anonymous FTP.

7.4.2 IGS Products

The products of all IGS analysis centers are archived at three global data centers. The combined official IGS products, currently orbits and pole only, may be found at the same locations. Other IGS products, like station data and SINEX files, are also available at the three IGS global data centers.

Within the IGS we strive to keep the internet load at a minimum. Everyone is therefore advised to access the nearest global data center. The three data centers are located at IGN (France), CDDIS (USA east coast) and SIO (USA west coast). Below we describe very briefly how to access these global data centers and where to find the IGS data and products.

To access IGN located in Paris, France use the following commands:

ftp	**mozart.ign.fr** -or- **192.33.147.225**
login	**anonymous**
password	*your full e-mail address*
data	**cd igs$core** followed by **cd ddd**
products	**cd igs$calc** followed by **cd wwww**

To access CDDIS located near Washington, USA use the following commands:

ftp	**cddis.gsfc.nasa.gov** -or- **128.183.10.141**
login	**anonymous**
password	*your full e-mail address*
data	**cd gps1:[gpsdata.yyddd.yyO]**
products	**cd gps3:[products.wwww]**

To access SIO located in California, USA use the following commands:

ftp	**toba.ucsd.edu** -or- **132.239.152.80**
login	**anonymous**
password	*your full e-mail address*
data	**cd /rinex/yydata/ddd**
products	**cd /products/wwww**

The IGS maintains the so-called *Central Bureau Information System* (CBIS). The primary functions of the CBIS are to facilitate communication, coordinate IGS activities, establish and promote compliance to IGS network standards, monitor network operations and quality assurance of data and maintain documentation. The CBIS is accessible through the Internet by anonymous ftp and the information is mostly available in easy to handle ASCII files. Alternative access methods are provided as well, such as third-party e-mail servers and a World Wide Web home page.

The CBIS can be accessed in the following ways:

ftp	**ftp igscb.jpl.nasa.gov** -or- **128.149.70.171**
www	**http:\\igscb.jpl.nasa.gov**
e-mail	**bitftp@pucc.princeton.edu**

For more information about the CBIS please send an e-mail to igscb@igscb.jpl.nasa.gov

8. Satellite Orbits

In the first section (motivation) we study the impact of orbit errors on the estimated station coordinates. We also include indications of precisions of the currently available orbit products (Broadcast Orbits, IGS Orbits, CODE Orbits). In Section 8.2 we present some of the basic concepts underlying the orbit part of the Bernese GPS Software Version 4.0 , the *key-words* being Keplerian orbit, osculating elements, orbit parameterization in Version 4.0 , variational equations, and numerical integration. Section 8.3 describes the individual programs dealing with orbits in Version 4.0 . Section 8.4, finally, reviews some experiences gained at the *CODE Analysis Center of the IGS* between 1992 and 1996.

8.1 Motivation

Until quite recently, the orbit quality was considered as one of the primary *accuracy limiting factors* in the applications of the GPS for geodesy and geodynamics. Since the *International GPS Service for Geodynamics* started its operations on June 21, 1992, this statement is no longer true. Orbits of an unprecedented accuracy are available today for all active GPS satellites with a delay of less than 12 days after the observations. Since January 1, 1996, so-called IGS preliminary orbits were made available only 36 hours after the observation; since 30 June (beginning of GPS week 860) this preliminary orbit is called *IGS Rapid Orbit* and is ready to be used only 24 hours after the observations, and the former Rapid Orbit is called *IGS Final Orbit* and it is made available 11 days after the observations.

What is the impact of this development? In order to answer this question we study the effect of *unmodeled orbit errors* on the estimated station coordinates. There is a crude, but handy *rule of thumb* which was derived a long time ago by [*Baueršíma*, 1983], giving the error Δx in a component of a baseline of length l as a function of an orbit error of size ΔX:

$$\Delta x(\mathrm{m}) \approx \frac{l}{d} \cdot \Delta X(\mathrm{m}) \approx \frac{l(\mathrm{km})}{25'000(\mathrm{km})} \cdot \Delta X(\mathrm{m}) \tag{8.1}$$

where $d \approx 25'000$ km is the approximate distance between the satellite system and the survey area. [*Zielinski*, 1988] is more optimistic (by a factor of 4-10) using statistical methods. For sessions of about 1-2 hours (and shorter) formula (8.1) gives satisfactory results [*Beutler*, 1992], for permanent site occupations the formulae given by [*Zielinski*, 1988] (based on statistics) seem to be more appropriate.

Table 8.1 gives the actual baseline errors in meters and in *parts per million (ppm)* for different baseline lengths and different orbit qualities as they have to be expected based on the above formula.

Orbit Error	Baseline Length	Baseline Error in ppm	Baseline Error in mm
2.5 m	1 km	.1 ppm	- mm
2.5 m	10 km	.1 ppm	1 mm
2.5 m	100 km	.1 ppm	10 mm
2.5 m	1000 km	.1 ppm	100 mm
.05 m	1 km	.002 ppm	- mm
.05 m	10 km	.002 ppm	- mm
.05 m	100 km	.002 ppm	- mm
.05 m	1000 km	.002 ppm	.5 mm

Table 8.1: Errors in Baseline Components due to Orbit Errors

What orbits are available today? Let us mention five types of orbits, namely *(a) Broadcast Orbits, (b) CODE Predicted Orbits, (c) CODE Rapid Orbits, (d) IGS Rapid Orbits, (e) IGS Final Orbits*. The estimated accuracies, based on analyses performed by the IGS Analysis Center Coordinator, are given in Table 8.2

Orbit Type	Quality (m)	Delay of Availability	Available at
Broadcast Orbits	3.00 m	Real Time	Broadcast Message
CODE Predicted Orbits	.20 m	Real Time	CODE through FTP
CODE Rapid Orbits	.10 m	after 16 hours	CODE through FTP
IGS Rapid Orbit	.10 m	after 24 hours	IGS Data Centers
IGS Final Orbit	.05 m	After 11 Days	IGS Data Centers and CBIS

Table 8.2: Estimated Quality of Orbits in 1996

The rms value of 20 cm per coordinate quoted for the CODE predicted orbit refers to a 2–4 hours extrapolation, 50 cm is the appropriate value for a 48 hours extrapolation.

8.2 Basic Theory

8.2.1 Celestial Mechanics

The Keplerian Orbit

The mathematical description of a satellite orbit would be very simple if the gravity field of the Earth were spherically symmetric, if the Earth were the only celestial body acting on the satellite, and if, moreover, *non-gravitational forces* like *air-drag* and *radiation pressure* would not exist. Maybe life on Earth would be problematic in this case, however.

Under these, circumstances the geocentric orbit $\mathbf{r}(t)$ of a satellite in *inertial space* is described by a simple differential equation system of second order in time, the so-called *equations of motion*, for the case of the *two-body problem* (actually even a *reduced* version of two-body problem because we will always be allowed to neglect the satellite's mass for the gravitational attractions):

$$\ddot{\mathbf{r}} = -GM\frac{\mathbf{r}}{r^3} \ , \tag{8.2}$$

where GM is the product of the constant of gravity and the mass of the Earth, r is the length of the geocentric radius vector $\mathbf{r}$ of the satellite.

It is well known that the solution of the equations of motion (8.2) is either an *ellipse*, a *parabola*, or a *hyperbola*. In our context we are obviously only interested in the first type of solutions. In Figure 8.1 we see one possible set of *six parameters* describing the orbit. It is exactly this set which is used for orbit characterization in the *Bernese GPS Software* (since the early days).

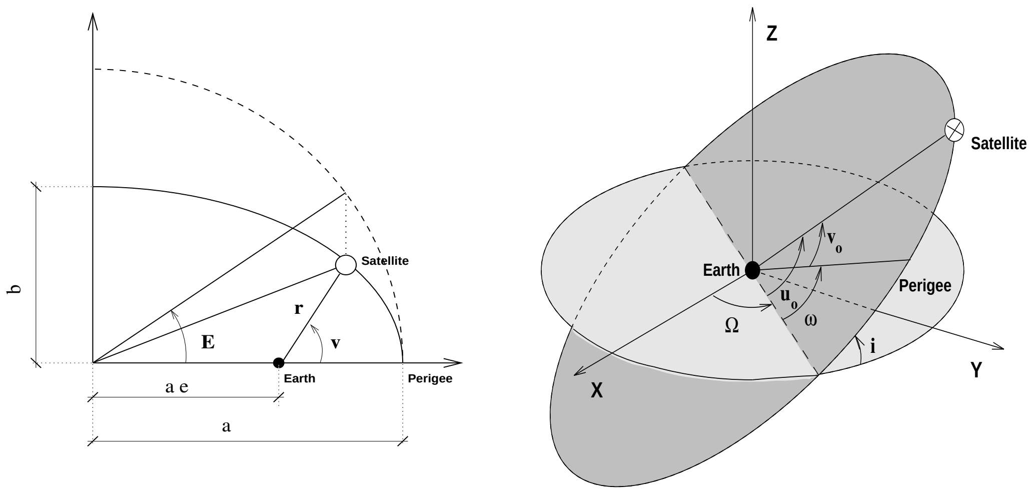

Figure 8.1: The set of orbital elements $a, e, i, \Omega, \omega, u_0$

Let us make a few comments concerning these orbital elements:

- a is the *semimajor axis* of the orbit, defining the size of the orbit.
- e is the *numerical eccentricity* or simply *eccentricity* of the orbit, describing the shape of the orbit.
- i is the inclination of the orbital plane with respect to the equatorial plane.
- Ω is the *right ascension of the ascending node*, i.e. the angle between the direction to the *vernal equinox* (X-direction in Figure 8.1) and the intersection line (into that direction where the satellite crosses the equatorial plane from the southern to the northern hemisphere) of the satellite's orbital plane with the equatorial plane. i and Ω are the *Eulerian angles* defining the orientation of the orbital plane in the equatorial system.
- ω is called the *argument of perigee*, the angle (in the orbital plane) between the ascending node and the perigee (measured in the direction of the motion of the satellite).
- u_0 is called the *argument of latitude*, the angle between the ascending node and the position of the satellite at the (initial) time t_0. We have $u_0 = \omega + v(t_0)$, i.e. the argument of latitude is equal to the sum of the argument of perigee and the true anomaly at time t_0.

The reader familiar with basic astronomy knows that the *vernal equinox*, defined as the intersection line of the *equatorial* and the *ecliptic* planes is not fixed in space due to precession and nutation. Therefore we have to specify a *reference epoch* for equator and equinox to make the inertial frame unique. At the CODE Analysis Center we consequently use the system J2000.0. In the early days of the *Bernese Software* we still used the system 1950.0, which is why both systems still may be selected (see Panel 3.2) essentially for compatibility purposes with older results. **For all new applications the system J2000.0 should be used**. For a precise definition of reference systems we refer to [*Seidelmann*, 1992] and [*McCarthy*, 1992].

The Osculating Orbit Elements

We know that the actual *equations of motion* are much more complicated than those of the one-body problem (8.2). For a real satellite we have to write instead:

$$\ddot{\mathbf{r}} = -GM\frac{\mathbf{r}}{r^3} + \mathbf{a}(t, \mathbf{r}, \dot{\mathbf{r}}, p_0, p_1, p_2, \ldots) = \mathbf{f}(t, \mathbf{r}, \dot{\mathbf{r}}, p_0, p_1, p_2, \ldots) \tag{8.3}$$

where we recognize the *two-body term* of the force field as the first term on the right hand side of eqn. (8.3). As opposed to eqn. (8.2), we have to take into account the *perturbation term* **a** under *real life conditions*. The perturbing acceleration **a** is characterized by many parameters (think e.g. of the Earth's gravity potential). The parameters $p_0, p_1, p_2, \ldots$ in eqns. (8.3) are those, which are not sufficiently known, but which have to be estimated in the orbit determination process. In the case of GPS satellites these parameters are usually associated with *radiation pressure* (see below).

The label *perturbation* implies that the two-body-term is dominant in the equations of motion (8.3). That this is actually true for our applications is illustrated by Table 8.3, where the most important acceleration terms acting on GPS satellites are characterized.

The fact that the perturbing accelerations are small (in absolute value) compared to the main (two-body) term makes the concept of *osculating orbital elements* a reasonable one. Osculating elements may be defined in the following way: Let us assume that we solve eqns. (8.3) through the method of numerical integration (see below). As a result we have readily available geocentric position and velocity $\mathbf{r}(t),\ \mathbf{v}(t)$ of the satellite for each time argument t which lies within the time interval over which the integration was performed. Now, we may *formally* assign one set of orbital elements $a(t)$, $e(t)$, $i(t)$, $\Omega(t)$, $\omega(t)$, and $u_0(t)$ to each epoch t by computing from the position and velocity vectors $\mathbf{r}(t),\ \mathbf{v}(t)$ the Keplerian elements using the formulae of the two-body problem. The resulting element set is called the *set of osculating elements at time t*. This may be done because there is a one-to-one correspondence between the position and velocity vectors and the Keplerian elements. In the Bernese GPS Software the subroutine XYZELE is used to compute elements from one set of position and velocity vectors, EPHEM is used for computing the mentioned vectors from elements. The osculating orbit (defined by the osculating elements) at time t is tangential to the actual orbit at time t. The actual orbit in a time interval $< t_1, t_2 >$ is the *envelope* of all the osculating orbits in this interval.

Perturbation	Acceleration m/s^2	Orbit Error after one Day (m)
Two-Body Term of Earth's Gravity Field	0.59	∞
Oblateness of Earth	$5 \cdot 10^{-5}$	$10'000$
Lunar Gravitational Attraction	$5 \cdot 10^{-6}$	3000
Solar Gravitational Attraction	$2 \cdot 10^{-6}$	800
Other Terms of Earth's Grav. Field	$3 \cdot 10^{-7}$	200
Radiation Pressure (direct)	$9 \cdot 10^{-8}$	200
Y-Bias	$5 \cdot 10^{-10}$	2
Solid Earth Tides	$1 \cdot 10^{-9}$	0.3

Table 8.3: Perturbing Accelerations acting on a GPS Satellite

The following figures show the osculating elements (except u_0) for GPS satellite PRN14 over a time interval of three days in the year 1995. We see very pronounced *short-period perturbations* (with periods of one satellite revolution period or smaller), most of them caused by the Earth's oblateness. Moreover we see *secular perturbations* in the right ascension of the ascending node Ω and *long-period perturbations* with periods of half a month for the inclination i (in addition to the short-period perturbations).

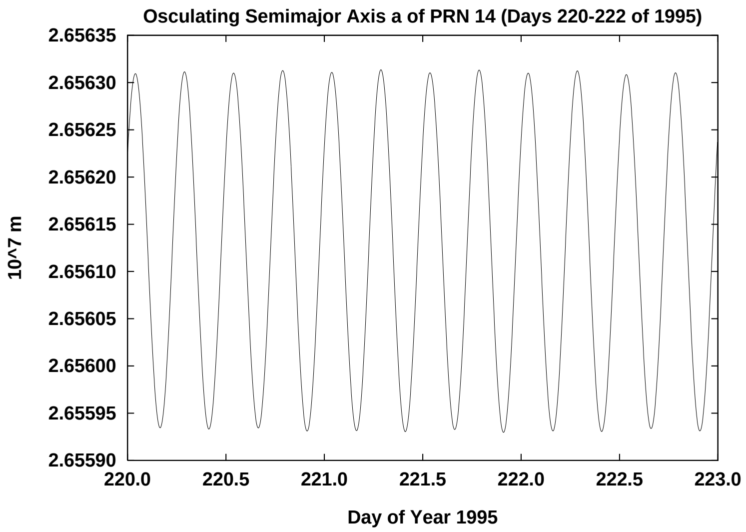

Figure 8.2: Osculating Semimajor Axis of PRN 14 During Three Days of Year 1995

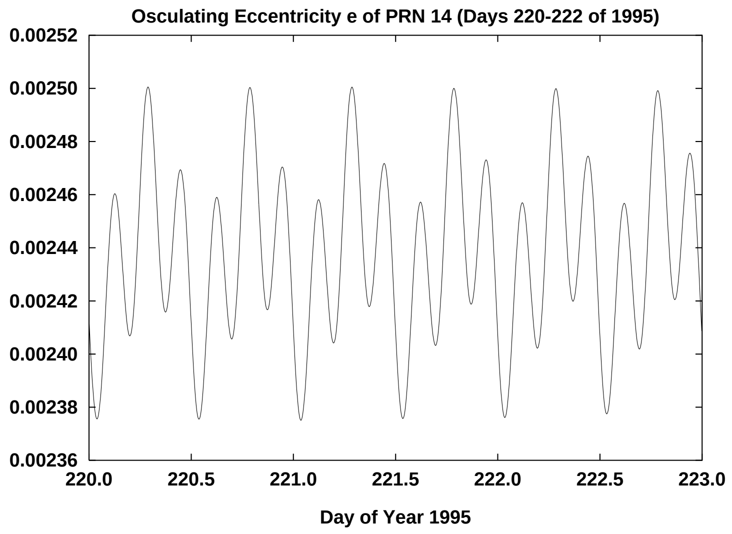

Figure 8.3: Osculating Eccentricity of PRN 14 During Three Days of Year 1995

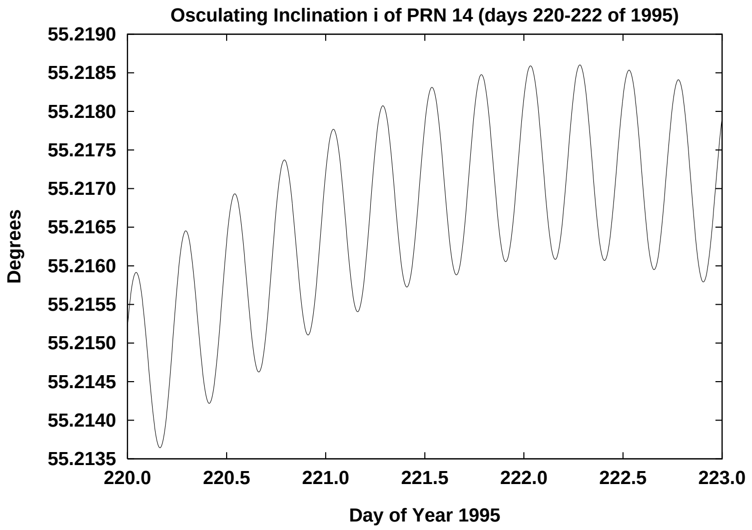

Figure 8.4: Osculating Inclination of PRN 14 During Three Days of Year 1995

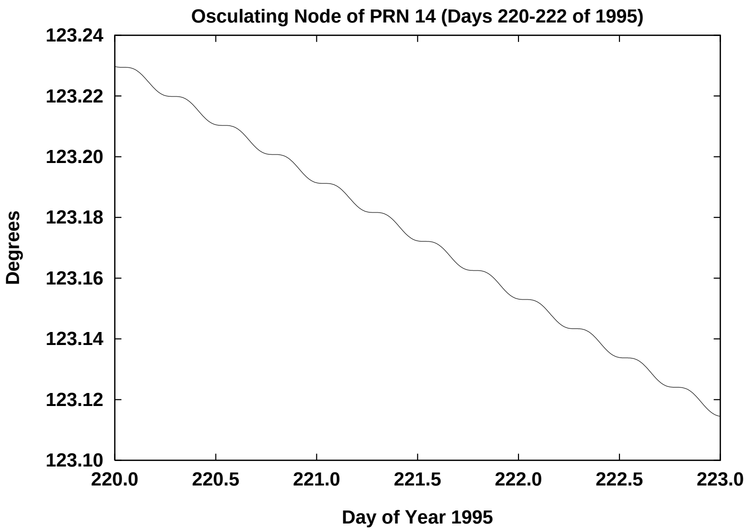

Figure 8.5: Osculating R.A. of Ascending Node of PRN 14 During Three Days of Year 1995

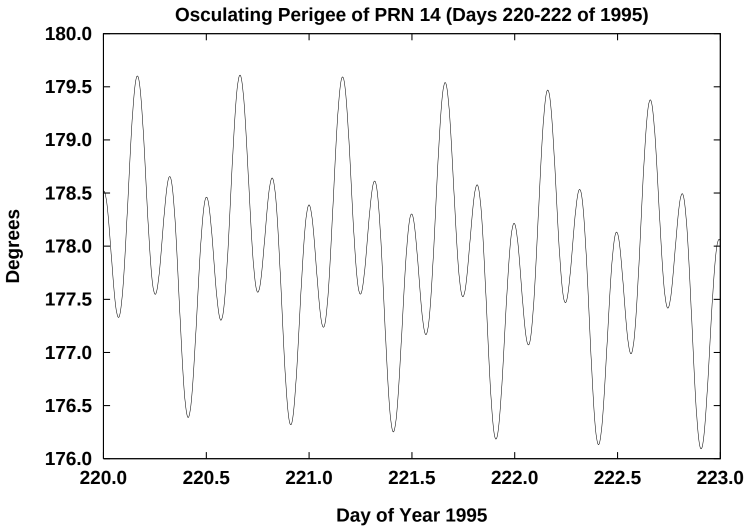

Figure 8.6: Osculating Argument of Perigee of PRN 14 During Three Days of Year 1995

From these perturbations in the elements we conclude that it is very convenient to think of the actual orbit as a time-series of osculating elements. We may e.g. follow very nicely the precession of the orbital plane and we have the impression that there are *only* short-period perturbations in the semimajor axis a.

That there are more complex perturbations involved becomes obvious if we study the *mean elements* (mean values of the elements over one revolution of the satellite) over longer time intervals. Figure 8.7 shows the development of the mean semimajor axis over three years (mid 1992 to fall 1995).

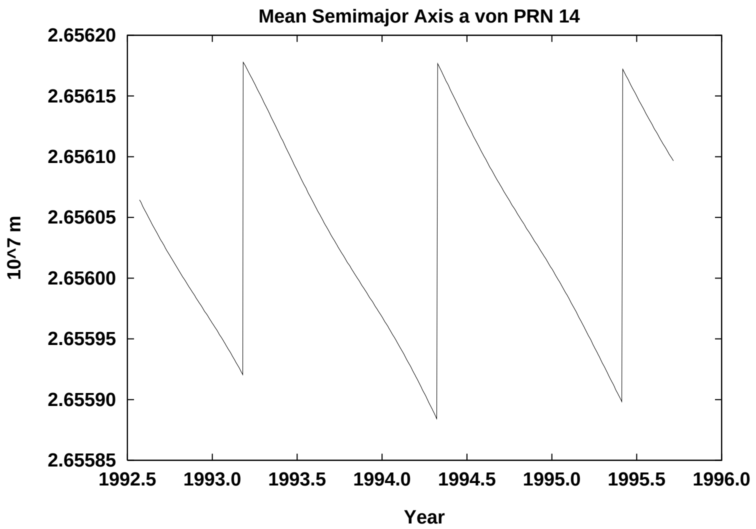

Figure 8.7: Osculating Semimajor Axis of PRN 14 Over Three Years

Figure 8.7 illustrates an essential characteristic of the GPS: There are very pronounced (very) *long-period perturbations* of the semimajor axes a of the satellites which are actually due to the resonance terms of the Earth's gravity field. These resonance perturbations require relatively frequent *manoeuvres* for the GPS satellites. We see three of these events in Figure 8.7. Without such manoeuvres (along-track pulses) the distribution of the satellites within the orbital plane could not be maintained uniform for a long time.

Orbit Parameterization (Deterministic Part)

When determining or characterizing the orbit of a satellite we *first* have to specify *six parameters* defining the position and the velocity vectors at the initial epoch t_0 of the arc. One might use the components of the vectors $\mathbf{r}_0 = \mathbf{r}(t_0)$ and $\mathbf{v}_0 = \mathbf{v}(t_0)$ for that purpose. In the *Bernese GPS Software* we use the *osculating elements of the initial epoch* t_0 to define the initial conditions: $a_0 = a(t_0)$, $e_0 = e(t_0)$, $i_0 = i(t_0)$, $\Omega_0 = \Omega(t_0)$, $\omega_0 = \omega(t_0)$, and $u_{00} = u_0(t_0)$.

Each orbit (or, to be even more precise, each arc) is a solution of the equations of motion (8.3). Many parameters are in principle necessary to solve these equations of motion: Most of the force field constituents of Table 8.3 are characterized by many parameters (think of the parameters necessary for the Earth's gravity potential!). So, in principle each orbit is characterized through six osculating elements and through *the set of all model parameters*. Most of these *dynamical* parameters are known with sufficient accuracy from other analyses (SLR in particular) and it is neither necessary (nor possible in most cases) to *improve* or *solve for* these parameters in GPS analyses. Of course, each orbit determination center has to tell what orbit models it uses and what numerical values are adopted for the parameters. Within the International GPS Service for Geodynamics (IGS) this is done through so-called *Analysis Centre Questionnaires*. We will include the questionnaire for the *CODE Analysis Center* in the last section of this chapter.

As mentioned previously the parameters $p_0, p_1, \ldots$ given explicitly in eqn. (8.3) are those dynamical parameters which – in general – have to be estimated for each arc and each satellite individually. If we assume that there are n_p such dynamical parameters, we may state that *the orbit or arc is parameterized through* $n = 6 + n_p$ *parameters*. When these parameters are known and if one and the same model is used for the *known* part of the force field everybody should be able to reconstruct one and the same trajectory $\mathbf{r}(t)$ of the satellite through numerical integration starting from time t_0 (see next section). *In this sense our* $n = 6 + n_p$ *orbit parameters uniquely specify a satellite orbit.*

What dynamical parameters do we use in the Bernese GPS Software Version 4.0 ? Let us first state that formally we attribute these parameters to radiation pressure (but we have to admit that other effects may be absorbed by them, as well).

According to [*Beutler et al.*, 1994] we write the radiation pressure model in the following way:

$$\mathbf{a}_{rpr} = \mathbf{a}_{ROCK} + \mathbf{a}_D + \mathbf{a}_Y + \mathbf{a}_X \tag{8.4}$$

where $\mathbf{a}_{ROCK}$ is the acceleration due to the Rock4 (Block I satellites) and Rock42 (Block II satellites) models for the radiation pressure [*Fliegel et al.*, 1992], and

$$\begin{array}{lclcl} \mathbf{a}_D & = & (a_{D0} + a_{DC} \cdot \cos u + a_{DS} \cdot \sin u)\mathbf{e}_D & = & D(u) \cdot \mathbf{e}_D \\ \mathbf{a}_Y & = & (a_{Y0} + a_{YC} \cdot \cos u + a_{YS} \cdot \sin u)\mathbf{e}_Y & = & Y(u) \cdot \mathbf{e}_Y \\ \mathbf{a}_X & = & (a_{X0} + a_{XC} \cdot \cos u + a_{XS} \cdot \sin u)\mathbf{e}_X & = & X(u) \cdot \mathbf{e}_X \end{array} \tag{8.5}$$

where

$a_{D0}, a_{DC}, a_{DS}, a_{Y0}, a_{YC}, a_{YS}, a_{X0}, a_{XC}$, and a_{XS} are the nine parameters of the radiation pressure model of the Bernese Software Version 4.0 ,

$\mathbf{e}_D$ is the unit vector sun-satellite,

$\mathbf{e}_Y = \dfrac{\mathbf{e}_D \times \mathbf{r}}{|\mathbf{e}_D \times \mathbf{r}|}$ is the unit vector along the space craft's solar-panels axis,

$\mathbf{e}_X = \mathbf{e}_Y \times \mathbf{e}_D$,

$D(u)$, $Y(u)$, and $X(u)$ are the total accelerations due to radiation pressure (on top of the Rock4/42–models) in the directions $\mathbf{e}_D$, $\mathbf{e}_Y$, and $\mathbf{e}_X$, and

u is the argument of latitude at time t for the satellite considered.

The radiation pressure model of Version 4 is a generalization of the standard radiation pressure model of Version 3 still used for the official CODE solutions. It contains *nine* instead of only *two* dynamical parameters for each satellite (and arc). Parameter a_{D0} corresponds to the direct radiation pressure parameter p_0 of the *old* model, parameter a_{Y0} corresponds to the y-bias parameter p_2 of the *old* model.

The *a priori term* $\mathbf{a}_{ROCK}$ in eqn. (8.4) needs a few additional comments because [*Fliegel et al.*, 1992] make subtle distinctions between different types of *ROCK models* and because, at CODE, different versions of the ROCK4/42 and different scaling methods were used in the past.

Since January 14, 1996, the start of GPS Week 836, the ROCK4/42 model, version T (including Thermal Re-radiation) is used at CODE. The a priori model is automatically scaled by the factor r_0^2/r^2, where r_0 is the Astronomical Unit (AU), and r is the actual distance between sun and spacecraft. *Prior to January 14, 1996* the S-Version of the ROCK4/42 model was used (S stands for standard) and *no* scaling was used for the term $\mathbf{a}_{ROCK}$.

In order to compute the actual accelerations acting on the satellite [*Fliegel et al.*, 1992] need to know the *satellite mass*. The satellite masses which are used since January 14, 1996 by the CODE Analysis Center are given (together with other satellite specific information like the antenna phase center eccentricity) in the file `SATELLIT.TTT` which is included in Table 8.4. The radiation pressure file descriptor *T950101* is also written into all the `*.ELE` files (see Chapter 23) by Version 4. If program ORBGEN is used in the update mode (see below) and the file descriptor in the `*.ELE` file does not match the one in the satellite file (e.g. `SATELLIT.TTT`), an error message is written by program ORBGEN and the program execution is stopped. The satellite information corresponding to CODE orbits prior to January 14, 1996 are contained in the satellite file `SATELLIT.OLD`.

```
SATELLITE SPECIFIC DATA                                              08-MAR-95
------------------------------------------------------------------------------
RADIATION PRESSURE MODEL : T950101    (ROCK MODEL T, FLIEGEL ET AL, 1992)

     BLOCK    ANTENNA OFFSETS (M)      MASS      DP0      P2     ROCK MODEL
PRN   NO.     DX       DY      DZ      (KG)    (1.E-8)  (1.E-9)   (T=1,S=2)

  1    3    0.2794  0.0000  1.0259     975.    -0.2132   0.5640      1    ok
  2    2    0.2794  0.0000  1.0259     878.2    0.0169   0.3178      1    ok
  3    3    0.2794  0.0000  1.0259     975.                          1    new
  4    3    0.2794  0.0000  1.0259     975.    -0.1072   0.7666      1    ok
  5    3    0.2794  0.0000  1.0259     975.    -0.1145   0.4401      1    ok
  6    3    0.2794  0.0000  1.0259     975.    -0.1410   0.8875      1    ok
  ...
```

Table 8.4: File “`SATELLIT.TTT`” of the Bernese Software, Version 4.0

In Table 8.4 you also find the correction term (`DP0`) to the direct radiation pressure which is added as a direct radiation pressure term (in the direction sun-satellite) to the a priori model. The same is true for the y-bias (column `P2`). The numerical values are based on an analysis of radiation pressure data for the years 1992 to 1994. The values, together with the ROCK4/42 term, are an excellent approximation for the actual radiation pressure parameters, in general.

In summary, in Version 4.0 of the Bernese GPS Software each satellite arc is characterized by *six* osculating elements and by *up to nine* dynamical parameters as defined above. The parameterization of the a priori orbits is defined in program ORBGEN (see below).

Orbit Parameterization (Pseudo-Stochastic Part)

Whereas the “normal” user of the *Bernese GPS Software* only has to deal with the $n = 6 + n_p \leq 15$ deterministic orbit parameters discussed in the previous section, the advanced user working in orbit determination might also wish to parameterize the orbits *in addition* with so-called *pseudo-stochastic parameters* which characterize instantaneous velocity changes at user-determined epochs in user-determined directions. The attribute *stochastic* is justified because usually *a priori weights (i.e. variances) are associated with these parameters*. In this sense the procedure is comparable to the stochastic orbit modeling used by other groups [*Zumberge et al.*, 1994]. The attribute *pseudo* is used because we are *not* allowing the orbits to adjust themselves continuously at every measurement epoch (as it is the case if Kalman filtering is used).

The use of pseudo-stochastic parameters proved to be a very powerful tool to improve the orbit quality. Until about mid 1995 pseudo-stochastic parameters were set up at CODE only for eclipsing satellites and for problem satellites (like PRN23), afterwards pseudo-stochastic pulses in *radial* and in *along-track* directions were set up for every satellite twice per day (at midnight and at noon UT). This clearly improved the CODE orbits. For more information we refer to [*Beutler et al.*, 1994].

8.2.2 Variational Equations

If the orbits of the GPS satellites are estimated using the *Bernese GPS Software* the partial derivatives of the position and velocity vectors with respect to all orbit parameters have to be computed by the program ORBGEN. Let us consider only the deterministic model parameters at present:

$$p \in \{a, e, i, \Omega, \omega, u_0, p_0, p_1, \ldots\} \tag{8.6}$$

We have to compute the partials

$$\mathbf{r}_p(t) = \frac{\partial \mathbf{r}(t)}{\partial p} \tag{8.7}$$

$$\mathbf{v}_p(t) = \frac{\partial \mathbf{v}(t)}{\partial p} \tag{8.8}$$

If the orbit were given by the eqns. of motion (8.2), it would be rather simple to compute the above partials (at least for the osculating elements): we know the position and velocity vectors "analytically" as functions of the osculating elements and therefore simply may take the partial derivatives of these known functions with respect to the orbit parameters. We gave explicit formulae e.g. in [*Beutler et al.*, 1996]. As a matter of fact the partials with respect to the osculating elements were approximated like that in Version 3 of the *Bernese GPS Software*.

We decided to compute all partials (8.7) and (8.8) rigorously in Version 4 using numerical integration because we were afraid that for longer arcs with more orbit parameters our analytical approximations might not be sufficient in all cases.

The procedure implemented in Version 4 is very simple in principle. We derive one set of differential equations called *variational equations*, and one set of initial conditions, for each orbit parameter p. Then we solve the resulting initial value problem through numerical integration (next section).

Although the procedure to derive variational equations is standard and may be found in many textbooks we include these variational equations for the sake of completeness. Let us start from the original initial value problem (8.3) and the associated initial conditions:

$$\ddot{\mathbf{r}} = -GM\frac{\mathbf{r}}{r^3} + \mathbf{a}(t, \mathbf{r}, \dot{\mathbf{r}}, p_0, p_1, p_2, \ldots) = \mathbf{f}(t, \mathbf{r}, \dot{\mathbf{r}}, p_0, p_1, \ldots) \tag{8.9}$$

$$\mathbf{r}_0 = \mathbf{r}(t_0; a, e, i, \Omega, \omega, u_0) \tag{8.10}$$

$$\mathbf{v}_0 = \mathbf{v}(t_0; a, e, i, \Omega, \omega, u_0) \tag{8.11}$$

By taking the derivative of the above equations with respect to parameter p we obtain the following initial value problem (variational equation and associated initial conditions):

$$\ddot{\mathbf{r}}_p = \mathbf{A} \cdot \mathbf{r}_p + \mathbf{f}_p \tag{8.12}$$

$$\mathbf{r}_{0,p} = \mathbf{r}_p(t_0; a, e, i, \Omega, \omega, u_0) \tag{8.13}$$

$$\mathbf{v}_{0,p} = \mathbf{v}_p(t_0; a, e, i, \Omega, \omega, u_0) \tag{8.14}$$

where we assumed that for GPS satellites there are no velocity-dependent forces. **A** is a 3×3 Matrix with $A_{p,ik} = \partial \mathbf{f}_i / \partial \mathbf{r}_k$, $\mathbf{f}_p$ is the explicit derivative of **f** with respect to the parameter p (equal to zero for osculating element). The initial conditions are zero for the dynamical parameters.

We thus have to solve one linear initial value problem for each unknown parameter p. This means that in general in Version 4 we have to deal with 16 initial value problems in the orbit generation step (one for the primary equations (8.3), 6 for the osculating elements, and 9 for all dynamical parameters).

What has to be done with the pseudo-stochastic parameters? It is very nice that the partials with respect to these parameters may be computed rigorously as linear combinations of the partials with respect to the osculating elements. This fact is a consequence of some properties of linear differential equation systems. It is thus *not* necessary to store additional information for the pseudo-stochastic parameters.

8.2.3 Numerical Integration

The initial value problem (8.9), (8.10), (8.11) (initial value problem associated with the *primary equations*) and the 15 linear initial value problems associated with the *variational equations* of type (8.12), (8.13), (8.14) are all solved using the technique of *numerical integration* in the *Bernese GPS Software Version 4*. The only program performing numerical integration is the program ORBGEN. It may be used to generate an orbit by fitting a set of tabular satellite positions (in the least squares sense) in an orbit determination process; it may also be used to update an orbit using the orbit parameters previously established by the programs GPSEST or ADDNEQ and written into a `*.ELE` file. In addition, it may be used as an orbit predictor – just by extending the *right boundary* of the (complete) integration interval.

The integration method used in program ORBGEN is a so-called *Collocation Method*. Let us briefly discuss the principles of such methods.

The entire integration interval is divided into *subintervals* of a user-specified length. To give an example: A one-day interval is e.g. divided into 24 one-hour subintervals. Within each subinterval (and for each of the 16 differential equation systems to be solved) an *initial value problem* is set up and solved, or, more precisely *numerically approximated*. In the *first subinterval* the initial value problems are precisely those defined in the previous section. In the *subsequent intervals* the initial values at the left subinterval boundary, let us call it t_l, are computed using the approximated solution of the *previous* subinterval. This subdivision of the integration interval was (probably) first proposed by *Leonhard Euler*.

How do we approximate the solution? Euler, in his simple algorithm, approximated each component of the solution vector by a polynomial of degree $q = 2$ by asking the approximating solution to go through the same initial values as the true solution and that the approximating solution satisfies the differential equation system at epoch t_l. Let us illustrate Euler's principle using the original initial value problem (8.9), (8.10), (8.11):

$$\mathbf{r}(t) = \mathbf{r}_0 + (t - t_0) \cdot \mathbf{v}_0 + \frac{1}{2} \cdot (t - t_0)^2 \cdot \mathbf{f}(t_0, \mathbf{r}_0, \mathbf{v}_0, \ldots) \tag{8.15}$$

The above solution vector may of course be used to compute the velocity vector, too, just by taking the time derivative of the formula for $\mathbf{r}(t)$:

$$\mathbf{v}(t) = \mathbf{v}_0 + (t - t_0) \cdot \mathbf{f}(t_0, \mathbf{r}_0, \mathbf{v}_0, \ldots) \tag{8.16}$$

Let us point out that the Eulerian formulae may be used to compute position and velocity at any point in the vicinity of the initial epoch t_0. A collocation method has exactly the same property. The only difference consists of the fact that instead of using polynomials of degree 2 we use higher degree polynomials in the case of general *collocation methods*:

$$\mathbf{r}(t) = \sum_{i=0}^{q} (t - t_0)^i \cdot \mathbf{r}_{0i} \tag{8.17}$$

where q is the degree of the polynomials, $\mathbf{r}_{0i}$ are the coefficients.

How are the coefficients $\mathbf{r}_{0i}$ determined? Well, this is the nucleus of numerical integration using collocation methods. The principle is very simple to understand and very closely related to Euler's method: The coefficients are determined by asking that the above approximation passes through the same initial values as the true solution, and that the differential equation system is satisfied by the approximating function at exactly $q-1$ different time epochs within the subinterval considered. The resulting condition equations are non-linear and in general have to be solved iteratively. Unnecessary to say that the integration algorithm was programmed to result in a efficient process.

We pointed out several times in this section that numerical integration actually should be called a numerical approximation of the solution. Whereas this is true in principle the remark is of rather academic value: If, in the case of GPS satellites, sub-interval lengths of 1 hour are used and if a polynomial degree (or integration order) of $q = 10$ is used the accumulated approximation error after three days is still below 1 mm in satellite position.

The integration process is completed by writing the polynomial coefficients for each satellite, each component and each subinterval into a so-called *standard orbit file* (`*.STD` file – see Chapter 23) and those for all the partials into the so-called *radiation pressure file*, the `*.RPR` file.

One of the reasons why in the earlier versions of the *Bernese GPS Software* the partials of the orbit with respect to the osculating elements were rather crudely computed using the Keplerian approximation was the size of the resulting radiation pressure file: If the coefficients for the partial derivatives are saved in the same way as those for the satellite positions, the file length of the `*.RPR` files would be 15 times the size of the `*.STD` files – which seemed to be a waste of disk space! This is true in particular if one takes into account that the accuracy requirements for the partials are by no means as stringent as those for the orbits.

The procedure that is now being used in Version 4 of our software seems to be an optimum: Whereas the variational equations are solved using *exactly the same interval subdivision and the same polynomial degree* as for the integration of the primary equations, it is possible and advisable to change the polynomial degree and the subinterval length for storing the coefficients associated with the variational equations. In practice we use a subinterval length of six hours and a polynomial degree of 12 for storing the coefficients for the partials. Through this procedure we have the partials in the files available with sufficient precision (6 to 8 significant digits) without wasting disk space. As a matter of fact the `*.RPR` files of Version 4 are of about the same size as those of Version 3 (but in Version 4 there are 15 partials, whereas there were only 3 in Version 3).

8.3 The Orbit Programs of the Bernese Software Version 4.0

Figure 8.8 gives an overview of the functions which may be performed with the orbit part of the software. There are six such functions, but actually there are eight FORTRAN programs behind these functions: The broadcast check may either be performed in an interactive way or by a pure batch program, the creation of tabular orbit positions in the inertial frame $J2000.0$ may either start form broadcast messages or (what is the normal case today) from precise orbit information.

```
 3   |                    ORBITS: OPTION MENU
-----+--------------------------------------------------------------
     |
-----+--------------------------------------------------------------
 1 ..| BROADCAST CHECK : Check Broadcast Ephemerides
 2   | CREATE TABULAR  : Generate Tabular Orbits from Broadcast/Precise
 3   | CREATE STANDARD : Generate/Update Standard Orbits
 6   | DIFF.  STANDARD : Display Differences between Standard Orbits
 7   | CREATE PRECISE  : Generate Precise Ephem. from Standard Orbits
 8   | SATELLITE CLOCKS: Generate Satellite Clock File
 9 ..| NEW ORBIT PROGR.: DEF093, UPD093, ORBIMP
```

Figure 8.8: Menu for Orbit Programs in Bernese Software Version 4.0

A functional flow diagram containing all essential steps that may be performed within the orbit part of Version 4.0 may be found in Figure 8.9.

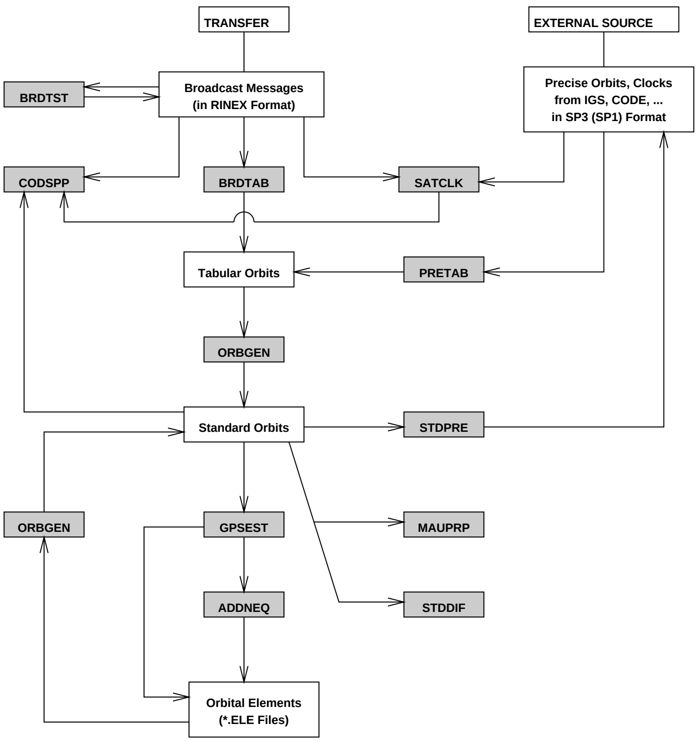

Figure 8.9: Flow Diagram of Orbit Part in Bernese GPS Software Version 4.0

Figure 8.9 asks for some comments. Let us look at three cases:

Case (a): You uniquely work with broadcast information and you do *not* improve orbits.

Case (b): You work with precise orbit information and you do *not* improve orbits.

Case (c): You work with either precise or with broadcast information and you want to improve orbits.

The first two cases are studied in the next subsection, orbit improvement is the topic in the subsequent subsection.

8.3.1 Using Orbit Information with Version 4.0

Case (a): Programs BRDCHK, BRDTST, and SATCLK

BRDCHK (Menu 3.1.1) is a very simple editor for broadcast ephemerides and clock parameters, BRDTST (Menu 3.1.2) is the automatic version of BRDCHK.

BRDCHK is an interactive program where you may eliminate satellite messages which are obviously wrong. An input and output broadcast file have to be specified (to be on the safe side, the input file is not altered). The program displays all messages of a satellite. You are asked whether or not you want to delete messages. If no more messages are deleted, the program proceeds to the next satellite. At the end, the remaining messages are written to the output file.

Let us mention that it is also easy to edit the broadcast files without BRDCHK: Files may be concatenated, separated, messages deleted. In this context it is important to know that the messages need not to be ordered according to satellites or according to times. The message number which is given for each message is ignored by the access routine (see also Chapter 23).

BRDTST is a batch program which is able to process more than one broadcast file in the same program run. For each file and each satellite the broadcast messages and the satellite clock parameters are checked for two different types of errors and one type of events:

(1) If a message or a clock parameter is obviously wrong (e.g. an inclination of 2 degrees) the status in the display is set to BAD A (bad semi major axis), BAD E (bad eccentricity), BAD I (bad inclination), ...

(2) If a message or a clock parameter has a reasonable value, but the difference to the corresponding element of the previous message is unreasonably big, the status is set to BAD DA, BAD DE, ...

(3) If the orbital elements in the messages show big jumps between two subsequent epochs but are consistent before and after this jump, it is assumed that the satellite was repositioned or manoeuvred. If such a jump is detected the satellite number, the precise epoch, etc. will be listed at the end of the program run and all the messages of this satellite after the jump will obtain a *new satellite number = old satellite number + 50*. This *artificial* satellite will then be treated like a normal satellite (see also Chapter 23).

In Table 8.5 we reproduce (part of) the output produced by program BRDTST for a particular program run.

Program BRDTAB (Menu 3.2) must now be used to transform the orbit information from the broadcast message into a set of tabular ephemerides in system B1950.0 or J2000.0, where we recommend to use uniquely the system J2000.0. You will have to use a POLE-file (see Panel 0.3.1 and Chapter 23) with information concerning the *earth rotation parameters* in program BRDTAB (and in program ORBGEN, below). You will probably use information which originally comes from the *IERS Bulletin A or B*.

The POLE-file has to be in the *Bernese format*. The file `RAP_YYYY.ERP` (`YYYY` stands for the current year), in the correct format may be retrieved through anonymous ftp (`ubeclu.unibe.ch`, directory `AIUB$FTP:[BSWUSER.GEN]` , see Chapter 7).

```
EPHEMERIS PARAMETERS FOR SATELLITE  3
-------------------------------------

NUM  STATUS   WEEK   TOE       A            E      ...    PER

  1           471  169200. 26560287.9  0.01169876  ...  149.332
  2  BAD A    471  172800.      296.1  0.01169863  ...  149.330
  3           471  176400. 26560295.5  0.01169862  ...  149.330
  4           471  255600. 26560328.6  0.01170016  ...  149.328
  5  BAD DE   471  259200. 26560341.2  0.01969999  ...  149.324
  6           471  262800. 26560336.0  0.01169990  ...  149.326
  .           ...  ......  ..........  ..........  ...  .......

CLOCK PARAMETERS FOR SATELLITE  3
---------------------------------
NUM STATUS WEEK   TOE     TOC         A0           A1           A 2
  1        471  169200. 169200. -0.721770D-07 0.100000D-11 0.000000D+00
  2        471  172800. 172800. -0.703150D-07 0.100000D-11 0.000000D+00
  3        471  176400. 176400. -0.684520D-07 0.100000D-11 0.000000D+00
  .        ...  ....... .......  ............ ............ ............
SUMMARY:
-------
SAT.  #MSG  #OK   #BAD  #JUMPS
  3     9     7     2      0
  6     6     6     0      0
  9    12    12     0      0
 11    13    13     0      0
 12    15    15     0      0
 13    11    11     0      0
NO JUMPS DETECTED
```

Table 8.5: Sample Output produced by Program BRDTST

SATCLK is a program extracting satellite clock information from broadcast files and writes it into a satellite clock file in the Bernese format (see Chapter 23). This program must be only used if you want to use in program CODSPP (see Chapter 10) a precise orbit file together with broadcast clock information. This is not a recommended option. Usually you should use the clock information which is in the corresponding precise orbit file (see also Chapter 16).

Using Precise Orbits (Program PRETAB)

Let us look at **Case (b)**, now: There is no program corresponding to programs BRDCHK and BRDTST for precise orbits (it is assumed that precise information actually is precise (!)).

You will use program PRETAB (corresponding to program BRDTAB) to create a tabular orbit file in the system $J2000.0$ (Menu 3.2). The POLE-file used (see Panel 0.3.1) must correspond to your orbit information. The correct file may also be retrieved from the subdirectory `BSWUSER` (in the same way as in the case of the Bulletin A pole, see Chapter 7).

You *will* in general produce a *satellite clock file* in Menu 3.2. You will fit the satellite clock information in the precise files within intervals of several hours (12 hours is recommended in Panel 3.2–1) by low degree polynomials (the recommended degree is $q = 2$) and thus create a satellite clock file which may be used to compute satellite clock corrections for each observation epoch. This way of handling the clocks in the precise files is called the *normal case* in Panel 3.2–1.

You also have the possibility to extract exactly the satellite clock corrections of the precise orbit files (usually given at 15 minute intervals) by asking for a polynomial degree and an interval length of "zero". In this case, for observations made exactly at the time of the tabular epochs in the precise orbit file, you may access the very precise IGS satellite clock information (thus circumventing Selective Availability SA). Program CODSPP is the only program which may take profit out of this *special case* for handling precise clock information *if* you are asking for the correct option in this program. For all other programs this option is very harmful due to the significant data reduction (one epoch every 15 minutes instead of every 30 seconds). Use this *special option with care*! For more information we refer to the description of program CODSPP (see Chapters 10 and 16).

Program ORBGEN for Cases (a) and (b)

You are now ready to use program ORBGEN. This program replaces the three programs DEFSTD, UPDSTD, and NEWSTD of the *Bernese Software Version 3*. All functions that were covered in Version 3 are options of the new program ORBGEN.

ORBGEN has the following general properties:

- The result of program ORBGEN is what we call a *standard orbit*.
- Each standard orbit may be composed of one or more *standard arcs*, each of which is characterized by a *start and an end time*.
- Each standard arc is a *solution of the equations of motion (8.3)* characterized by six initial conditions and a *user-specified number of dynamical parameters*. A maximum of nine deterministic parameters per satellite are possible. Standard orbits generated via an orbital element file may be characterized *in addition* by stochastic pulses.
- The *multi-arc* option was of vital importance in the early releases of Version 3, when program GPSEST was the only parameter estimation program (for high accuracy results). Each observation that was used in GPSEST had to be *covered* by exactly one standard orbit. **Today we strongly recommend to work with only one standard arc per standard orbit and to combine data from different days, campaigns, etc. with program** ADDNEQ (see Chapter 18). The use of program ADDNEQ based on multi-arc standard orbits is *not* recommended.
- If you want to perform orbit determination in programs GPSEST and ADDNEQ you have to produce in program ORBGEN a file containing the partial derivatives, too (`*.RPR` file).

- All standard orbits and all partial derivatives (variational equations) are computed by numerical integration in program ORBGEN. ORBGEN is the only program in Version 4 in which numerical integrations are performed.

Because ORBGEN replaces three programs of Version 3 there must be several options in ORBGEN:

- ORBGEN may be used to generate a standard orbit *starting from tabular satellite positions*. The user selects the processing options (and we refer to the help panels for recommendations). ORBGEN will use all the tabular satellite positions – within the interval for which standard arcs were requested – as *pseudo-observations* in an orbit determination process (one such process per arc and satellite). The user has to select the model parameters: All six initial values (actually osculating elements) and a suitable combination of the nine *dynamical parameters*. We will give different recommendations below for different types of tabular positions (broadcast or precise). Each standard arc of the resulting standard orbit will be a particular solution of the equations of motion (8.3) best fitting the mentioned tabular satellite positions.
- ORBGEN may be used to *update* a standard orbit using the information in an orbital element file. You may then say whether you actually want to use the updated orbits or if you want to *reconstruct the a priori orbit* which was used for this particular time interval (usually one day) for the orbit improvement (see Panel 3.3–2.1). The program ORBGEN will make sure that the same `SATELLIT`-file (see Chapter 23) is used in the update step as in the orbit determination step. The stochastic pulses which are (also) stored in the `*.ELE` files are taken into account.
- ORBGEN may be used as an *orbit prediction program* in both of the above program options, by just specifying the right interval boundary. If you use this option in the update mode (with an orbital element file `*.ELE`) you should be aware of the fact that there can be *no other* pseudo-stochastic pulses applied than those in the `*.ELE` file (no extrapolation into the future). Let us mention that the complete radiation pressure model (nine parameters) without stochastic pulses is well suited for predictions if you use program ORBGEN starting from tabular orbit files `*.TAB` (see program output, below). When generating a standard orbit using tabular positions, you may also extend the integration interval into the past (by shifting the left integration boundary).

Program ORBGEN will always produce a summary concerning the fit of the tabular orbit positions. If you were using tabular files stemming from broadcast messages such a summary (in the second iteration step) will look roughly as follows:

```
RMS ERRORS AND MAX. RESIDUALS   ARC NUMBER:  1          ITERATION:  2
----------------------------------------------------------------------
                      QUADRATIC MEAN OF O-C (M)     MAX. RESIDUALS (M)
SAT  #POS  RMS (M)  TOTAL   RADIAL  ALONG   OUT    RADIAL  ALONG   OUT
---  ----  -------  ----------------------------  --------------------
  1    44    1.88    1.82     1.90   1.84   1.71    3.04   4.68   3.68
  2    44    0.70    0.68     0.94   0.49   0.52    1.29   1.45   0.89
  3    44    1.57    1.52     1.81   1.89   0.26    3.97   5.44   0.45
 ..    ..    ....    ....     ....   ....   ....    ....   ....   ....
 31    44    0.75    0.73     1.08   0.46   0.46    1.67   1.25   0.89
```

Table 8.6: Output produced by Program ORBGEN with classical Radiation Pressure Model using Tabular Positions stemming from Broadcast Messages

Table 8.6 shows that the internal *consistency* of the broadcast orbits was around 1 meter (the actual accuracy is around three meters, as mentioned). Table 8.6 was produced using the *classical* orbit model with eight parameters (six osculating elements, 2 radiation pressure parameters) which is sufficient to accomodate broadcast orbits.

Table 8.7 shows that the fit is of the order of 5–10 cm if *a precise IGS ephemerides file* is used to generate the `*.TAB` file and if the standard orbit model (with the six osculating elements and the two radiation pressure parameters a_{D0} and a_{Y0}) is used.

If we use our new model with all nine parameters, the orbital fit is much better, of the order of 1 cm rms, only (Table 8.8). **In order *not* to loose the precision of the precise orbits we thus recommend to solve for all nine dynamical parameters of the new model to create the standard orbits whenever starting from precise orbit information.**

```
-----------------------------------------------------------------------
RMS ERRORS AND MAX. RESIDUALS   ARC NUMBER:  1            ITERATION:  2
-----------------------------------------------------------------------
                      QUADRATIC MEAN OF O-C (M)      MAX. RESIDUALS (M)
SAT  #POS   RMS (M)  TOTAL   RADIAL  ALONG   OUT    RADIAL  ALONG   OUT
---  ----   -------  ----------------------------   -------------------
  1    96     0.07    0.07     0.08   0.09   0.02    0.24   0.28   0.04
  2    96     0.04    0.04     0.04   0.05   0.03    0.12   0.13   0.05
  4    96     0.05    0.05     0.04   0.08   0.01    0.08   0.18   0.03
 ..    ..     ....    ....     ....   ....   ....    ....   ....   ....
 ..    ..     ....    ....     ....   ....   ....    ....   ....   ....
 ..    ..     ....    ....     ....   ....   ....    ....   ....   ....
 31    96     0.08    0.08     0.08   0.11   0.03    0.24   0.31   0.07
------------------------------------------------------------------------
```

Table 8.7: Output produced by Program ORBGEN with classical rpr Model

```
-----------------------------------------------------------------------
RMS ERRORS AND MAX. RESIDUALS   ARC NUMBER:  1            ITERATION:  2
-----------------------------------------------------------------------
                       QUADRATIC MEAN OF O-C (M)     MAX. RESIDUALS (M)
SAT  #POS   RMS (M)  TOTAL   RADIAL  ALONG   OUT   RADIAL  ALONG   OUT
---  ----   -------  ---------------------------   --------------------
  1    96     0.01    0.01     0.01   0.01   0.01    0.05   0.02   0.02
  2    96     0.01    0.01     0.01   0.01   0.00    0.02   0.03   0.01
  4    96     0.01    0.01     0.01   0.01   0.00    0.03   0.02   0.01
 ..    ..     ....    ....     ....   ....   ....    ....   ....   ....
 ..    ..     ....    ....     ....   ....   ....    ....   ....   ....
 ..    ..     ....    ....     ....   ....   ....    ....   ....   ....
 31    96     0.01    0.01     0.01   0.01   0.01    0.04   0.02   0.02
-----------------------------------------------------------------------
```

Table 8.8: Output produced by Program ORBGEN using full new orbit Model

In Chapter 16 dealing with satellite and receiver clock information, we will discuss an interesting use of program CODSPP based on clock information available in the IGS precise orbit files by just taking over this information from the precise ephemerides file. This can be achieved in Menu 3.2 by putting polynomial degree and interval length to zero for the clock extraction in Panel 3.2–1. CODSPP will be able to make a very accurate single point positioning (sub-meter accuracy using data from one day). Because satellite positions (and clocks) are only available every 15 minutes in the precise orbit files, this program option automatically leads to a very significant data decimation (instead of e.g. one observation/30 seconds) you will only have available one observation every 15 minutes, *not only for code but also for phase observations*. This is *not* sufficient for a secure preprocessing of phase data. Therefore this option is **not** recommended for normal processing.

Service Programs STDPRE and STDDIF

Both programs are very simple to use, the handling is fully explained by the corresponding help panels.

Program STDPRE (Menu 3.7) is used to generate a precise orbit file in the official precise orbit format defined by [*Remondi*, 1989]. Precise orbit files contain satellite positions (and velocities) in an earth-fixed system (e.g. ITRF94). For the transformation from the inertial frame (standard orbit) to the earth-fixed frame (precise orbit) a pole file consistent with the orbit information has to be used.

Program STDPRE is used every day at CODE to generate the official CODE products. You may also wish to use this program to send a precise orbit file (ASCII-file) corresponding exactly to your standard orbit to colleagues working on a different computer environment. If you also send them the pole-file you used in STDPRE, your colleagues will be able to reproduce *exactly* the standard orbit you used (through PRETAB, ORBGEN). (Another possibility is the conversion of the standard orbit file to an ASCII file – see Chapter 20 – to attain the same goal).

Optionally an orbital element file containing the improvement and rms errors of the orbital elements from GPSEST or ADDNEQ may be added when running STDPRE. Using this additional information an approximate orbit precision code will be written into the precise orbit file (only for SP3 format). The `SATCRX` file (satellite problem file – see Chapter 23) may be used in case of manoeuvres to identify which satellite number (PRN or PRN+50) has to be used to get the correct standard orbit information for epochs before and after the manoeuvre.

The program STDDIF (Menu 3.6) is used for study purposes to create a table of coordinate differences of two standard orbit files. The coordinate differences are listed in radial, along-track, and out-of-plane direction. Again we refer to the corresponding help panels.

8.3.2 Estimating Orbits with Version 4 (Case (c))

Orbit improvement was an important issue for the *normal user* asking for highest precision *before* the International GPS Service for Geodynamics started its operations in 1992. Today, orbit improvement *cannot be recommended for the normal user*, because it is close to impossible to come up with significantly better orbits than those produced by the IGS. Orbit improvement of course still is an issue if you process *old* GPS data (prior to 1992) or if you work actually as an *IGS Analysis Center*.

We will confine ourselves in this section to a few general remarks for the *expert user* and we refer to the CODE Annual Reports for 1994 and 1995 for more information [*Rothacher et al.*, 1995a, 1996a].

Let us first state that *if you improve orbits* it is in principle *not* important whether you start from broadcast or precise orbit information to create an a priori standard orbit. You should be aware of the fact, however, that the a priori orbit really matters, because the orbit improvement process is based on the linearization of a non-linear parameter estimation problem. Linearization means that you neglect higher order terms in the Taylor series (for the orbits as a function of the orbit parameters). The better your a priori orbit, the less important are the neglected terms of the linearization. If your a priori orbit is *only* good to about 20 m you should definitely go through a second iteration step (repeat the orbit improvement with the orbit generated in the first iteration step, which is now certainly within 0.1 m of the final results).

In program ORBGEN you have the possibility to use a complex or a relatively simple orbit representation for the a priori orbit. We recommend that you parameterize your orbit in ORBGEN only by eight parameters (osculating elements at initial epoch, direct radiation pressure and y-bias), *but that you store the partial derivatives with respect to all 15 parameters in the* `*.RPR` *file*. By following this recommendation you will have the possibility to *switch* from the *old* orbit model to the *new* one very easily on the level of the normal equation systems (ADDNEQ).

The actual orbit determination (improvement) has to be set up in program GPSEST. We recommend to use program GPSEST with data spans of *at maximum one day*. If you actually want to produce longer arcs, use program ADDNEQ to combine the one-day arcs.

In order to preserve all options for future runs with program ADDNEQ we recommend that you set up all 15 orbit parameters of the new model for every satellite in program GPSEST, but that you tightly constrain all the dynamical parameters to zero, *except* the two parameters of the old radiation pressure model. The one-day arc generated with program GPSEST thus will refer to the old orbit model, but formally (for future combinations) you have all 15 parameters available. Figure 8.10 shows the program options we recommend to specify in Panel 4.5–2.3 for the orbit characterization in program GPSEST for the establishment of a one-day arc.

In addition, you can see in Figure 8.10 that we recommend to set up pseudo-stochastic pulses in the middle of your arc (for one-day arcs at noon) (see Figure 8.11).

We can see that all parameters are set up as unknowns, but that only the osculating elements, the direct radiation pressure, and the y-bias are free to adjust.

```
4.5-2.3                  PARAMETER ESTIMATION: ORBITS

  Orbital Elements:                           (a priori sigmas)
    SEMI MAJOR AXIS      > YES <  (YES,NO)     > 0.000     <   m
    ECCENTRICITY         > YES <  (YES,NO)     > 0.0000000 <
    INCLINATION          > YES <  (YES,NO)     > 0.0000    <   arc sec
    ASCENDING NODE       > YES <  (YES,NO)     > 0.0000    <   arc sec
    PERIGEE              > YES <  (YES,NO)     > 0.0000    <   arc sec
    ARG. OF LATITUDE     > YES <  (YES,NO)     > 0.0000    <   arc sec

  Dynamical Parameters:                       (a priori sigmas)
    D0 estimation (P0)   > YES <  (YES, NO)    > 0.D-00    <   m/s**2
    Y0 estimation (P2)   > YES <  (YES, NO)    > 0.D-00    <   m/s**2
    X0 estimation        > YES <  (YES, NO)    > 1.D-12    <   m/s**2

  Periodic Dynamical Parameters:              (a priori sigmas)
    Periodic D0 terms    > YES <  (YES, NO)    > 1.0D-12   <   m/s**2
    Periodic Y0 terms    > YES <  (YES, NO)    > 1.0D-12   <   m/s**2
    Periodic X0 terms    > YES <  (YES, NO)    > 1.0D-12   <   m/s**s

  Stochastic Parameters: > YES <  (YES,NO)
```

Figure 8.10: Orbit Characterization for One-Day Arcs in Program GPSEST

```
4.5-2.3.1 | PARAMETER ESTIMATION: STOCHASTIC ORBIT PARAMETERS

Default values:
   Force Types (max. 3 types allowed):          A-priori Sigma

     (1)  RADIAL                                 > 1.D-09   <
     (2)  PERPENDICULAR TO (1), IN ORBIT PLANE   > 1.D-09   <
     (3)  NORMAL TO ORBIT PLANE                  > 1.D-09   <  (0 or blank:
     (4)  DIRECTION TO THE SUN                   >          <   don't take)
     (5)  Y-DIRECTION IN SATELLITE FRAME         >          <
     (6)  X-DIRECTION IN SATELLITE FRAME         >          <

   Number of sets per day:                           > 2  <

List of Satellites (prn numbers, 99(=ALL), 98(=ECL), 97(=ECLspec)):
    (blank field = take default values)

  GROUP      #PAR       SIGMA1          SIGMA2          SIGMA3

  > 99 <     > 2  <     >          <     >          <     >          <
```

Figure 8.11: Stochastic Parameter Selection in Program GPSEST

```
4.8.1-2.0 | ADD NORMAL EQUATION SYTEMS: ORBITS

   Orbital Elements:                            (a priori sigmas)
     SEMI MAJOR AXIS      > YES <  (YES,NO)     > 0.00      <   m
     ECCENTRICITY         > YES <  (YES,NO)     > 0.000000  <
     INCLINATION          > YES <  (YES,NO)     > 0.00      <   arc sec
     ASCENDING NODE       > YES <  (YES,NO)     > 0.00      <   arc sec
     PERIGEE              > YES <  (YES,NO)     > 0.00      <   arc sec
     ARG. OF LATITUDE     > YES <  (YES,NO)     > 0.00      <   arc sec

   Dynamical Parameters:                        (a priori sigmas)
     D0 estimation (P0)   > YES <  (YES, NO)    > 0.0D-00   <   m/s**2
     Y0 estimation (P2)   > YES <  (YES, NO)    > 0.0D-00   <   m/s**2
     X0 estimation        > YES <  (YES, NO)    > 1.0D-12   <   m/s**2

   Periodic Dynamical Parameters:               (a priori sigmas)
     Periodic D0 terms    > YES <  (YES, NO)    > 0.0D-00   <   m/s**2
     Periodic Y0 terms    > YES <  (YES, NO)    > 0.0D-00   <   m/s**2
     Periodic X0 term     > YES <  (YES, NO)    > 1.0D-12   <   m/s**2

   Orbit combination:
     LONG ARCS            > YES <  (YES,NO)
     INDIVIDUAL DYN. PAR. > NO  <  (YES,NO)

   Stochastic Parameters: > YES <  (YES,NO)

   Block rotation of orbital planes:
     X-AXIS               > NO  <  (YES,NO)
     Y-AXIS               > NO  <  (YES,NO)
     Z-AXIS               > NO  <  (YES,NO)
```

Figure 8.12: Orbit Characterization in Program ADDNEQ

You can see that pseudo-stochastic pulses are set up in radial, along-track, and in out-of-plane directions, but that they are actually constrained to (almost) zero for the actual parameter determination in GPSEST. If one-day arcs are your final result, you would probably allow for radial and along-track pulses in this panel (using the same values as in program ADDNEQ, see Figure 8.13 below). Let us point out that by "number of sets per day = 2" you actually set up one set every 12 hours, i.e. actually only one set per 24 hours (because the boundaries do not count). Keep in mind that you should also estimate earth rotation parameters when you determine the satellite orbits. More information on this topic may be found in Chapter 14.

After having executed program GPSEST with observations covering one day you have (among many other result files) (a) an orbital element file `*.ELE`, (b) a normal equation file `*.NEQ`, and (c) earth rotation parameter file `*.ERP` (results of the ERP estimation) at your disposal.

If one-day orbits (arcs) are your desired results you may now use the files `ELE` and `ERP` in program ORBGEN (update mode) to produce the corresponding `STD` file and generate a precise orbit file `PRE` with program STDPRE using files `STD`, `ERP`, and `ELE` (the latter file is "only" used to transfer accuracy information into the `PRE` file) and your job is finished.

If you want to create *longer than one-day arcs* or if you want to produce arcs (one-day or longer) with a different orbit parameterization you may now use program ADDNEQ with a sequence of `*.NEQ` files as input. Figure 8.12 shows that you may now re-consider the orbit modeling.

In the particular example of Figure 8.12 a more general orbit characterization was selected (it is possible to do that if previously the corresponding parameters were set up, but constrained in GPSEST). By asking for long arcs you will generate a three-day arc if you use program ADDNEQ with three `*.NEQ` files corresponding to three consecutive days. Otherwise ADDNEQ would assume that you wish to process the three days together, but with completely separate arcs for each day.

You can also see in Figure 8.13 that you are able to re-consider the stochastic parameters. The following Figure 8.14 will show, that you are even allowed to introduce new stochastic parameters at the arc-boundaries! This is a very nice example for the flexibility of program ADDNEQ.

```
4.8.1-2.1 |      ADD NORMAL EQUATION SYSTEMS: STOCHASTIC ORBIT PARAMETERS

Default values:
   Force Types (max. 3 types allowed):           A-priori Sigma

     (1)  RADIAL                                  > 1.D-6    <
     (2)  PERPENDICULAR TO (1), IN ORBIT PLANE    > 1.D-5    <
     (3)  NORMAL TO ORBIT PLANE                   > 1.D-9    <  (0 or blank:
     (4)  DIRECTION TO THE SUN                    >          <   don't take)
     (5)  Y-DIRECTION IN SATELLITE FRAME          >          <
     (6)  X-DIRECTION IN SATELLITE FRAME          >          <

List of Satellites (prn numbers, 99(=ALL), 98(=ECL)):
    (blank field = take default values)

     GROUP        SIGMA1           SIGMA2           SIGMA3

     > 99 <     >          <     >          <     >          <
```

Figure 8.13: Stochastic Parameter Selection in Program ADDNEQ

You see that in the particular example of Figure 8.13, as before in GPSEST, the pulses in the out-of-plane directions are constrained, but that the pulses in radial and along-track directions are allowed (within the constraints specified above). The same pulses are set up and solved for at the day boundaries (Figure 8.14)

```
4.8.1-2.A       ADD NORMAL EQUATION SYSTEMS: STOCHASTIC ORBIT PARAMETERS II

    Additional stochastic parameters at arc boundaries:
    Force Types                                   A-priori Sigma

      (1)  RADIAL                                  > 1.D-6    <
      (2)  PERPENDICULAR TO (1), IN ORBIT PLANE    > 1.D-5    <  (0 or blank:
      (3)  NORMAL TO ORBIT PLANE                   > 1.D-9    <   not used)

    LIST OF SATELLITES (svn numbers, ALL, STOCHastic, NONECLipsing):

    > ALL                                                         <
```

Figure 8.14: Additional Stochastic Parameter Selection in Program ADDNEQ

In order to demonstrate that the actual work at an Orbit Determination Center may be quite involved (mainly due to the fact that the data have to be screened and validated) we briefly recollect here the actual procedure to produce a three-day arc at the CODE processing center:

Production of a three-day arc at CODE:

- The a priori orbit is taken over from the generation of the CODE Rapid Orbit (16-hours Orbit); the a priori orbit always corresponds to the old orbit model.
- All single-difference files of the day are processed in GPSEST by modeling the correlations correctly on the *baseline level*, only. No stochastic parameters left free, old orbit model used.
- The residuals with respect to this "first" one-day arc are checked for outliers, bad phase observations are marked (see Chapter 20, program RESRMS)
- With these screened observation files, GPSEST is invoked again, again in the single baseline mode, but this time stochastic orbit parameters are opened up at noon.
- The new one-day arc is used to resolve ambiguities on the single baseline level using the *QIF-strategy* (see Chapter 15).
- After ambiguity resolution a new (already very precise) a priori orbit *without* stochastic parameters is defined and used for the remaining one-day solutions. This orbit is then also the basis for all three-day solutions.
- Again, we use GPSEST, and again we set up all 15 orbit parameters, but we tightly constrain all of them except the eight classical parameters. Moreover, we do *not* process the entire one-day data set in one program run, but we produce five cluster solutions (European, American, Australian, Asian+African, and "what remains"), where within each cluster (corresponding to one run of program GPSEST) the correlations are modeled correctly, and the ambiguities resolved previously are introduced as known.
- The five cluster solutions are superposed using program ADDNEQ to give *the final one-day solution*.
- Three consecutive `*.NEQ` files corresponding to the final one-day solutions are combined to give the final three-day solution.
- Any number of "different" solution series may now be produced using ADDNEQ, only [*Rothacher et al.*, 1995*a*, 1996*a*].

8.4 Experiences made with the Bernese Software at the Code Analysis Center of the IGS

CODE, the Center for Orbit Determination in Europe, is one of at present seven Analysis Centers of the *IGS, the International GPS Service for Geodynamics*. CODE is a joint venture of

- the Astronomical Institute of the University of Bern (AIUB),
- the Swiss Federal Office of Topography (L+T),
- the German Institute for Applied Geodesy (IfAG), and
- the French Institut Géographique National (IGN).

The CODE Analysis Center is located at the AIUB in Bern.

Since June 21, 1992, ephemerides for all active GPS satellites and daily values for the earth rotation parameters (x and y coordinates of the pole position, and drift values for UT1–UTC) are solved for and made available to the scientific community by *CODE*. Since January 1, 1994, the drifts $\Delta\dot{\psi}$ and $\Delta\dot{\epsilon}$ in the nutation corrections are determined as well. These values are constrained to zero for the official CODE solutions but may be activated for pure research purposes.

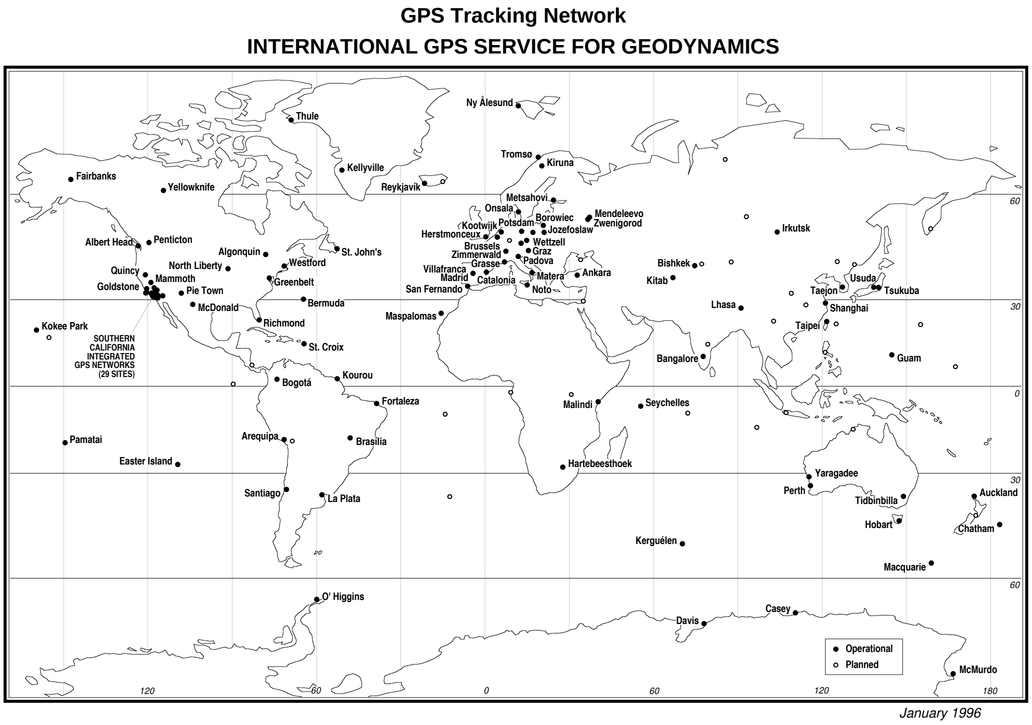

Figure 8.15: IGS Permanent Tracking Network in 1996

In addition annual coordinate (and velocity) solutions are sent every year since 1992 to the IERS [*Rothacher et al.*, 1994, 1995*a*]. These annual solutions are based on the correct combination of normal equation systems [*Brockmann*, 1996]. They are believed to be accurate to about 3-5 mm in the horizontal position, to about 1 cm in the vertical position. The quality of station velocities depends on the length of the data span available. With the three years of data that have been analysed now, the accuracy is of the order of ≈ 1 mm/year for the horizontal positions.

At present (July 1996) the data of about 80 stations of the *International GPS Service for Geodynamics (IGS) Network* (Figure 8.15) are analysed every day at CODE. Back in 1992 the CODE Analysis Center started by analyzing about 25 stations. The quality of the products (orbits, earth rotation parameters, station coordinates, troposphere parameters, etc.) is a function of the number of stations analysed, their distribution on the globe, and the quality of the processing software.

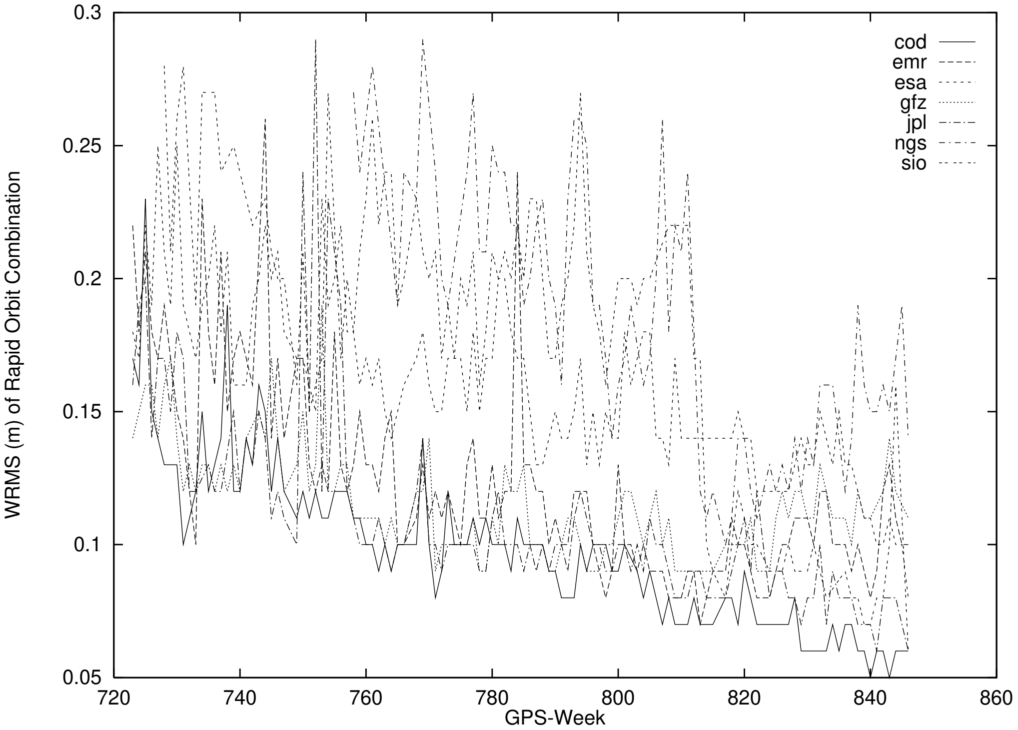

Figure 8.16: Orbit Quality of IGS Analysis Centers

Figure 8.16 gives an impression of the orbit quality achieved in this global project with the *Bernese Software Version 4*. It is certainly not exaggerated to state that the CODE contribution is of a very high quality (at least in the time interval covered by Figure 8.16).

The quality of the CODE products increased considerably since 1992: Initially the orbit quality was perhaps of the order of about 50-70 cm, whereas today we are approaching the 5 cm level (Figure 8.16), a number which is also confirmed by comparing our orbits with SLR observations to the GPS satellites equipped with LASER reflectors.

Table 8.9 contains a list of essential events/improvements of the *Bernese GPS Software* which were always instantaneously tested very carefully by the CODE processing center.

Epoch	Event	In V 4.0
Jun-92	Start of routine operations at CODE with Version 3.4	—
Nov-92	Monthly a priori coordinate sets	—
Jun-93	Pseudo-stochastic parameters for eclipsing satellites	YES
Sep-93	Version 3.5 implemented	—
Dec-93	Estimate 12 (instead of 4) troposphere parameters per day	YES
Jan-94	Transition to ITRF92	—
Apr-94	Store 1 day normal equations	—
Oct-94	3-day-solutions computed by combining 1-day NEQs	YES
Jan-95	Transition to ITRF93	—
May-95	Efficiency of GPSEST, ADDNEQ improved by a factor ≈ 10	YES
Jun-95	Use correct correlations in clusters	YES
	Weekly free network solutions in SINEX format	YES
	Submit ambiguities fixed solutions	YES
	Stochastic parameters for all satellites	YES
Oct-95	First CODE clock solutions submitted	YES
Nov-95	Version 4.0 used for official solutions	YES
Jan-96	Daily global ionosphere models produced	YES
	New orbit model implemented	YES
Jan-96	CODE rapid orbits (12 h after obs) produced	YES

Table 8.9: Development of the CODE Solutions using the Bernese GPS Software

The Analysis Center Questionnaire of the CODE Analysis Center of the IGS is included for the sake of completeness. It contains all (not only the orbit) processing characteristics of CODE (state of July 1996):

```
============================================================================


                  INTERNATIONAL GPS SERVICE FOR GEODYNAMICS

                      CODE Processing Strategy Summary


============================================================================
Analysis Centre    CODE (Center for Orbit Determination in Europe)
                   Astronomical Institute, University of Berne,
                   Sidlerstrasse 5, CH - 3012 Berne, Switzerland
                   Phone: ++ 41 31 631 85 91 , Fax: ++ 41 31 631 38 69
----------------------------------------------------------------------------
Contact Person(s)  Markus Rothacher  e-mail: rothacher@aiub.unibe.ch
                                     phone : ++ 41 31 631 85 92
                   Tim Springer      e-mail: springer@aiub.unibe.ch
                                     phone : ++ 41 31 631 85 92
----------------------------------------------------------------------------
Software Used      Bernese GPS Software Version 4.0, developed at AIUB
----------------------------------------------------------------------------
```

```
----------------------------------------------------------------------------
Final Products     CODwwwwn.EPH    GPS ephemeris/clock files in 7 daily
generated for                      files at 15 min intervals in SP3 format,
GPS week 'wwww'                    including accuracy codes computed from
day of week 'n'                    a long arc analysis of the last 7 solut.
(n=0,1,...,6)      CODwwww7.ERP    ERP (pole, UT1-UTC) solutions for 1 week
                   CODwwww7.SUM    Processing summary for 1 week

                   The files above contain the estimates for the middle
                   day of the 3-days solution.

Rapid Products     CODwwwwn.EP1    CODE 1-day orbit solution. 4-day delay
                   CODwwwwn.ER1    CODE 1-day pole solution to be used with
                                   the 1-day orbit

                   CODwwwwn.EPH_R  CODE rapid orbit solution. 12-hour delay
                   CODwwwwn.ERP_R  CODE rapid pole solution to be used with
                                   the rapid orbit

Predictions        CODwwwwn.EPH_P  CODE 24-hour orbit predictions. To be used
                                   in real time.
                   CODwwwwn.ERP_P  CODE predicted pole solution to be used
                                   with the 24-hour predicted orbit

                   CODwwwwn.EPH_P2 CODE 48-hour orbit predictions. To be used
                                   in real time.
                   CODwwwwn.ERP_P2 CODE predicted pole solution to be used
                                   with the 48-hour predicted orbit

----------------------------------------------------------------------------
Preparation Date   August 18, 1996
----------------------------------------------------------------------------
Effective Date for June 30, 1996
Data Analysis
============================================================================
```

```
----------------------------------------------------------------------------
                           MEASUREMENT MODELS
--------------------------------------------------------------------------
 Preprocessing     Phase preprocessing in a baseline by baseline mode
                   using triple-differences. In most cases cycle slips
                   are fixed looking simultaneously at different linear
                   combinations of L1 and L2. If a cycle slip cannot be
                   fixed reliably, bad data points are removed or new
                   ambiguities are set up.
                   A check of the postfit residuals is performed after
                   the first 1-day solution. Outliers are removed.
--------------------------------------------------------------------------
 Basic Observable  Carrier phase, code only used for receiver clock sync.
                  -------------------------------------------------------
                   Elevation angle cutoff :  20 degrees
                   Sampling rate          :   3 minutes
                   Weighting              : 1.2 cm for double-diff. iono-
                                            sphere-free LC. Satellites
                                            may be deweighted
--------------------------------------------------------------------------
 Modelled          Double-differences, ionosphere-free linear combination
 observable
--------------------------------------------------------------------------
 RHC phase         Phase polarization effects applied (Wu et al, 1993)
 rotation corr.
--------------------------------------------------------------------------
```

```
-----------------------------------------------------------------------------
Ground antenna    Elevation-dependent phase center corrections are
phase centre      applied according to the model IGS_01. The corrections
calibrations      are given relative to the Dorne Margolin T antenna.
-----------------------------------------------------------------------------
Troposphere       A priori model  : Saastamoinen (standard atmosp. used),
                                    including the mapping by Saastamoinen
                 ----------------------------------------------------------
                  Met data input  : none
                 ----------------------------------------------------------
                  Estimation      : zenith delays in 2 hour resp. 6 hour
                                    intervals for 1-day resp. 3-days sol.
                  Mapping function: 1/cos(z), z:zenith angle
-----------------------------------------------------------------------------
Ionosphere        Not modelled (ionosphere eliminated by forming the
                  ionosphere-free linear combination of L1 and L2).
                  Global ionosphere models are used in the ambiguity
                  resolution step.
-----------------------------------------------------------------------------
Plate motions     ITRF94 station velocities fixed for the 13 core sites
                  (at present TIBD and SANT not fixed, antenna change !)
-----------------------------------------------------------------------------
Tidal             Solid earth tidal displacement: IERS Standards 1992
displacements     Permanent tidal term          : applied in tide model,
                                                  NOT included in site
                                                  coordinates
                 ----------------------------------------------------------
                  Pole tide                     : not applied
                 ----------------------------------------------------------
                  Ocean loading                 : not applied
-----------------------------------------------------------------------------
Atmospheric load. Not applied
-----------------------------------------------------------------------------
Earth orientation Tidal UT1 (> 5 days): modeled
models (EOP)      Subdaily EOPs       : RAY model applied (IERS, 1996)
-----------------------------------------------------------------------------
Satellite center  Block I      x,y,z:  0.2100, 0.0000, 0.8540 m
of mass          ----------------------------------------------------------
correction        Block II/IIA x,y,z:  0.2794, 0.0000, 1.0259 m
-----------------------------------------------------------------------------
Satellite phase   Not applied
centre calibrat.
-------------------------------------------------------------------------------
Relativity        Periodic, -2(R*V/c): applied
corrections       Gravity bending    : not applied
                  Dynamical          : applied (IERS, 1996, Ch.11, Eq.1)
-------------------------------------------------------------------------------
Time argument     TDT
-------------------------------------------------------------------------------
GPS attitude      not applied
model
-------------------------------------------------------------------------------
```

```
-------------------------------------------------------------------------------
                             ORBIT MODELS
-----------------------------------------------------------------------------
Geopotential      JGM3 model up to degree and order 8  (+C21+S21)
                 ----------------------------------------------------------
                  GM = 398600.4415 km**3/sec**2
                 ----------------------------------------------------------
                  AE =   6378.1363 km
-----------------------------------------------------------------------------
```

```
----------------------------------------------------------------------------
 Third-body        Sun and Moon as point masses
                  ---------------------------------------------------------
                   Ephemeris: S. Newcomb "Tables of the Sun"
                  ---------------------------------------------------------
                   GMsun  = 132712500000 km**3/sec**2
                  ---------------------------------------------------------
                   GMmoon =    4902.7890 km**3/sec**2
----------------------------------------------------------------------------
 Solar radiation   Direct radiation: ROCK4 and ROCK42 approximations (T10
 pressure                            and T20) for Block I and II satell.

                   Satellite masses used:
                    PRN 01    878.2 kg    PRN 16-19 883.2 kg
                        12    519.8           20    887.4
                        14    887.4       PRN 21    883.9 kg
                        15    885.9           23    972.9
                    all other satellites            975.0 kg
                  ---------------------------------------------------------
                   One scale factor and the y-bias estimated per arc
                  ---------------------------------------------------------
                   Earth shadow model includes: cylindric shadow
                  ---------------------------------------------------------
                   Reflection radiation: not included
                  ---------------------------------------------------------
                   New GPS satellite attitude model: not applied
----------------------------------------------------------------------------
 Tidal forces      Solid earth tides: frequency independent Love's
                   number K2= 0.300
                  ---------------------------------------------------------
                   Ocean tides: not applied
----------------------------------------------------------------------------
 Relativity        Applied (IERS 1996, Chapter 11, Eqn.1)
----------------------------------------------------------------------------
 Numerical         Integration algorithms developed at AIUB by Gerhard
 Integration       Beutler (see references below). Representation of the
                   the orbit by a polynomial of degree 10 for 1 hour
                  ---------------------------------------------------------
                   Integration step: 1 hour
                  ---------------------------------------------------------
                   Starter procedure: no special starter procedure needed
                  ---------------------------------------------------------
                   Arc length: 72 hours
------------------------------------------------------------------------------
```

```
------------------------------------------------------------------------------
               ESTIMATED PARAMETERS (APRIORI VALUES & SIGMAS)
----------------------------------------------------------------------------
 Adjustment        Weighted least-squares algorithms
----------------------------------------------------------------------------
 Station           13 stations heavily constrained (0.1 mm) to the ITRF94
 coordinates       positions as given in IERS TN #20, the remaining
                   stations estimated. The ITRF94 velocities are used for
                   monthly coordinates updates.
                   A priori station constraints are removed to compute
                   multi-day coordinate solutions of all sites.
                   Currently two stations (TIDB and SANT) not fixed due
                   to recent antenna changes.
----------------------------------------------------------------------------
```

```
--------------------------------------------------------------------------
 Satellite clock   Satellite clock biases are not estimated but elimi-
 bias              nated by forming double-differences.
                   Satellite clocks are estimated in a post-processing
                   step using only code observations and the results
                   (ERPs, orbits, coord., troposphere) of the 3-day solut.
--------------------------------------------------------------------------
 Receiver clock    Receiver clock corrections are estimated during the
 bias              pre-processing using code measurements.
                   Receiver clocks are estimated in a post-processing
                   step using only code observations and the results
                   (ERPs, orbits, coord., troposphere) of the 3-day solut.
--------------------------------------------------------------------------
 Orbital           6 Keplerian elements at start of arc; solar radiation
 parameters        scale factor and y-bias estimated as constants for one
                   arc. No a priori sigmas used.
                   A priori orbits are predictions of the CODE rapid
                   orbit solution.
                   Pseudo-stochastic orbit parameters (small velocity
                   changes, constrained to 1.E-6 m/sec in radial and to
                   1.E-5 m/sec in along-track direction) are estimated
                   once per revolution for ALL satellites.
--------------------------------------------------------------------------
 Troposphere       Zenith delays estimated once per 6 hours for each
                   station. Corrections to a priori model constrained to
                   10 cm.
--------------------------------------------------------------------------
 Ionospheric       Not estimated
 correction
--------------------------------------------------------------------------
 Ambiguity         Ambiguities are resolved in a single baseline mode
                   using the QIF strategy (only phase observations used)
                   and global ionosphere models. Resolution only for
                   baselines shorter than 2000 km. About 85% of the
                   ambiguity parameters are resolved on these baselines.
                  -------------------------------------------------------
                   Average of fixed ambiguities (%): 50%  (all baselines)
--------------------------------------------------------------------------
 Earth Orient.     X- and Y-pole coordinates, and UT1-UTC estimated each
 Parameters (EOP)  as a polynomial of degree 1 over 3 days. UT1-UTC fixed
                   to the a priori values at the beginning of the first
                   day.
                   No a priori sigmas used. A priori values taken from
                    the CODE rapid orbit solution.
                    All reported EOP solutions do NOT include the subdaily
                   EOP model. The estimates are averages over the time
                   interval of the solution (3 days).
                    Drifts in nutation (Dpsi, Deps) are estimated in a
                    special 3-day solution, but are constrained to the
                    IAU 1980 model for the official CODE solution.
--------------------------------------------------------------------------
 GPS attitude      none estimated
 model
--------------------------------------------------------------------------
 Other             Center of mass coordinates are estimated for each
 parameters        3-day solution but with heavy constraints of
                   0.0001 meters for each coordinate.

----------------------------------------------------------------------------
```

```
----------------------------------------------------------------------------
                            REFERENCE FRAMES
--------------------------------------------------------------------------
 Inertial           Geocentric; mean equator and equinox of 2000 Jan 1
                    at 12:00 (J2000.0)
--------------------------------------------------------------------------
 Terrestrial        ITRF94 reference frame realized through the set of 13
                    station coordinates and velocities as given in IERS TN
                    #20 and the antenna heights for the above stations
                    given in /igscb/station/tie/localtie.tab available
                    from IGS CB (sideshow.jpl.nasa.gov).
                    Currently two stations (TIDB and SANT) not fixed due
                    to recent antenna changes.
--------------------------------------------------------------------------
 Interconnection    Precession: IAU 1976 Precession Theory
                   -------------------------------------------------------
                    Nutation: IAU 1980 Nutation Theory
                   -------------------------------------------------------
                    Relationship between UT1 and GMST: USNO Circular
                    No. 163 (IAU Resolution)
                   -------------------------------------------------------
                    EOP interpolated from IERS Bulletin A (updated every
                    week). No celestial pole corrections applied.
                   -------------------------------------------------------
                    Tidal variations in UT1: periods > 5.8 days modeled
                                             but not removed (UT1-UTC sol.)
----------------------------------------------------------------------------
```