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DIORAMA Model of Satellite Body Orientation

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Summary

The DIORAMA GPS satellite platform orientation model is described. Satellites need to keep sensors pointed towards the earth and solar panels oriented to face the sun (when not in the earth's shadow) while they orbit the earth.

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1 Introduction

A GPS satellite orientation is governed by two constraints [1]. First, the navigation and various sensor antennae should point towards the earth geocenter, and second, the normal to the solar array surface should point towards the sun. These two constraints require a satellite to constantly adjust its yaw attitude angle. The GPS satellite orientation is characterized by three angles: roll, pitch and yaw. Typically, working satellites maintain zero roll and pitch angles, and a constantly adjusting yaw angle. Yaw orientation can affect geophysical applications including precise point-positioning [2] and sensor sensitivity.

In addition to the nominal yaw angle adjustment that achieves the two constraints, differing GPS satellite platform types perform differing yaw adjustment maneuvers during special conditions and also have differing machine hardware maximum yaw rate capabilities. Special maneuvers may include noon and midnight turn maneuvers, earth's shadow crossing maneuver, and a post shadow recovery maneuver. The "noon" and "midnight" terms refer to the points in a satellite orbit of the earth where the satellite is closest to and farthest from the sun. Turn maneuvers feature changed behavior before and after the middle of the turn. Additionally, shadow crossing maneuvers may be broken up into sub-phases characterized by a spin-up or spin-down time to achieve the maximum yaw rate and operation at the maximum yaw rate. The yaw angle model is fairly complicated and is governed by equations given in references [1, 2]. In the coding of the yaw angle model for DIORAMA, each equation is accompanied by a comment that identifies the reference and equation number being evaluated.

The present manuscript describes not the detailed equations, but rather the general logic of the DIORAMA computer code's satellite body orientation model that characterizes the roll, pitch, and yaw at a specified time for a given satellite type and a two-line element (tle) representation of the orbit.

2 Body Orientation Model

The DIORAMA body orientation model computes the roll, pitch, and yaw angles of a GPS satellite at a specified time. This section describes the computation logic and identifies the required input data.

2.1 Satellite Orbit (tle), Time, and Position

The GPS satellite body orientation model requires the identification of the satellite and its orbit via specification of the satellite two-line element (TLE) set of orbit parameters. The TLE is specified in the DIORAMA scenario file as a body location. The TLE can be applied to compute the satellite position as a function of time and, equivalently, to compute the satellite orbit. The time of an event is specified in the DIORAMA scenario file by the event time parameter.

2.2 β Angle and Solar Position

The model for the satellite yaw angle is a function of four parameters: β, μ, type, and machine maximum yaw rate. The first two parameters are a function of the satellite orbit, time, and/or position. The β angle is defined as the angle between the unit vector from the earth to the sun and the plane containing the satellite orbit. Figure 1 illustrates the earth, sun, and satellite orbit geometry along with the useful angles of interest. The solar position model is described in [4].

Step 1. Calculate β angle,
by calling Diorama function $betaAngle(tle, t)$ as a function of tle and time, t.

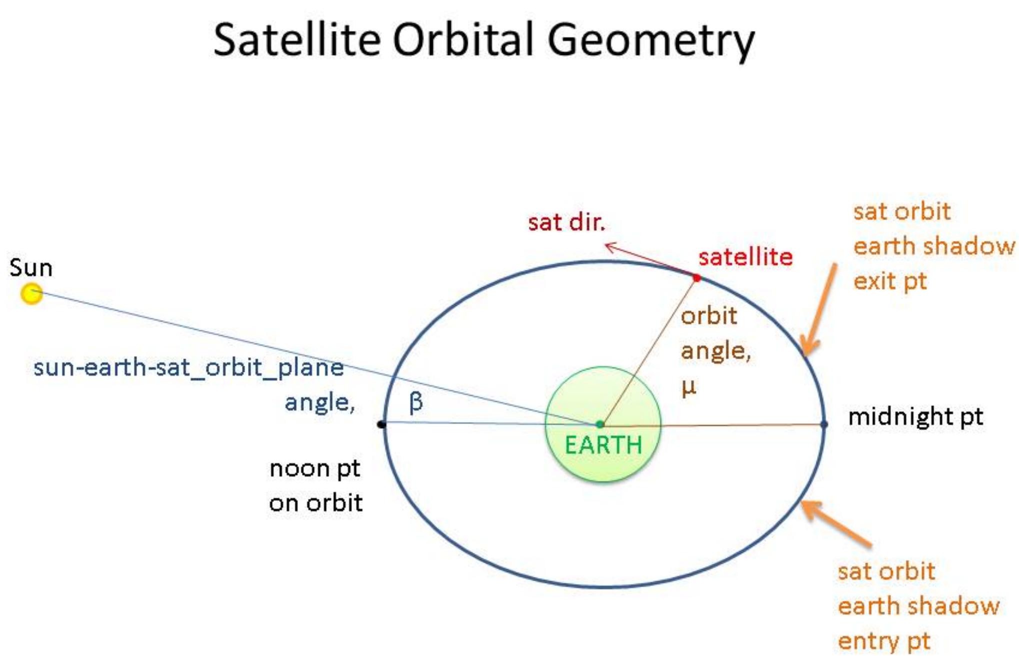
Step 1.1. Compute the unit vector from the earth to the sun, s,
by calling Diorama function $SunPositionFromEarth(t)$ as a function of time, t.

Step 1.2. Compute the satellite position unit vector, p,
by calling Diorama function $TLE\_Time2Location(tle, t)$ as a function of tle and time, t, and convert position to ITRF x,y,z coordinates, and normalize.

Step 1.3. Compute the satellite velocity unit vector, v,
by calling Diorama function $TLE\_Time2Location(tle, t + \epsilon)$ as a function of time, $t + \epsilon$, and convert position to ITRF x,y,z coordinates and normalize, and construct $v = p(t + \epsilon) - p(t)$, and renormalize to get a unit vector.

Step 1.4. Compute β from $\mathbf{s} \cdot (\mathbf{p} \times \mathbf{v}) = sin(\beta)$

Figure 1.



2.3 μ Angle and Midnight Point

The orbit angle, μ, is defined as the angle between the orbit midnight point and the present satellite position, growing with satellite motion. The μ angle is automatically computed as a second step of the *betaAngle*() function. The first step in computing μ, is to find the midnight point. The midnight point is defined as the point in an orbit that is farthest from the sun. The midnight point is found by using the satellite orbit propagator to find ITRF orbit positions; then correcting for earth rotation to get the position (x,y,z) in the earth reference frame of the event; then computing the distance from the sun. A two-sided, two-step bisection algorithm is applied to iterate to converge on the location of the midnight point. Because the sun is located so far from the earth, care must be taken avoid the situation where the convergence criterion is not smaller than the computer accuracy.

Step 2. Calculate μ angle,

by calling Diorama function $betaAngle(tle, t)$ as a function of tle and time, t.

Step 2.1. Compute the orbit midnight position unit vector, m,

by computing orbit positions, with a bisection iteration to find the farthest orbital point from the sun.

Step 2.2. Compute μ from $\mathbf{p} \cdot \mathbf{m} = cos(\mu)$,

checking to ensure that the arccos function result is in the correct quadrant.

2.4 Satellite Type and NORAD Number

The satellite TLE consists of three lines of data typically named Label, Line1, and Line2. The Label contains the satellite type and Line2 contains the unique NORAD number. Both the type and the NORAD number are passed into the function to compute the Yaw angle.

Step 3. Retrieve the satellite type and NORAD number from the tle.

Step 3.1. Extract the satellite type,

by calling Diorama function $getSatTypeAndPrn(tleLbl)$ as a function of tle Label.

Step 3.2. Extract the NORAD number,

by calling Diorama function $getNoradNum(Line2)$ as a function of tle Line2.

2.5 Yaw Angle

Maximum yaw rate, the fourth parameter in the satellite yaw angle model, is determined by using the NORAD number to look up the value from the data listed in Appendix Table A. The roll and pitch angles are assumed to be maintained at 0. If the type is "dsp", assume a Nadir model and return a randomly generated yaw angle. If the type is "iii", compute the yaw angle as if it were a type iif platform. Elsewise, apply detailed models for satellite types ii, iia, iir, and iif. First, the nominal yaw angle is computed. This is the yaw angle if the satellite is not performing any special maneuver, including noon and midnight turn maneuvers, earth's shadow crossing maneuver, and a post shadow recovery maneuver.

Next, the model determines if the satellite is performing any special maneuvers, and, if so, applies special models to compute the yaw angle. The complex logic used to determine if the satellite is performing a special maneuver is a function of satellite type, sun position and satellite orbit position. Table 1 summarizes this logic. The parameter β_0 is a function of the machine maximum yaw rate limit. In the coding of the yaw angle model for DIORAMA, each equation is accompanied by a comment that identifies the reference and equation number being evaluated.

Step 4. Calculate yaw angle,
by calling Diorama function yawAngle(type,norad,β,μ) as a function of satellite type, norad identifier, β, and μ.

- Step 4.1. Apply type and NORAD number to get the machine maximum yaw rate, by looking up the value from Appendix Table A.
- Step 4.2. Compute the nominal yaw value.
- Step 4.3. Determine if satellite is performing any special maneuvers, by applying logic summarized in Table 1.
- Step 4.4. Calculate and return the yaw angle.

Table 1. Yaw Angle Model Logic

```
//yaw angle Calculator timing logic (for beta=constant)
//
//yawAngle(beta,mu)
//{  while mu<pi/2,    mu+=2pi          //set mu bounds
//   while mu>pi*3/2, mu-=2pi
//   tt=mu/mudot                         //est current time
//1. calc yawn                           //calc nominal yaw
//   if(beta>=beta0 && type==iir)  return yawn
//2. if(beta>=beta0) calc tns            //calc noon maneuver start time
//     if(tt<tns)  return yawn
//     if(tns<tt<tns+60)
//       step thru/interpolate to get either
//         a. yaw  -> return yaw
//         b. tne                        //calc noon maneuver exit time
//3. if(beta<beta0 && type==iir/f)  calc tms  //calc midnite maneuvr start
//     if(tt<tms)  return yawn
//     if(tms<tt<tms+60)
//       step thru/interpolate to get either
//         a. yaw  -> return yaw
//         b. tme                        //calc midnight maneuver exit time
//4. if(type==ii/iia)
//     calc tss                          //calc shadow (entry) start time
//     calc tse                          //calc shadow exit time
//     if(tt<=tss || tt>tse+60)  return yawn
//     if(tt>tss && tt<tse)              //calc shadow maneuver
//       calc dtsp                       //calc spin up delta time
//       if(tt>tssd&&tt<tss+dtsep)
//         calc and return yaw
//       if(tt>tss+tsp)
//         step thru/interpolate to get either
//           a. yaw  -> return yaw
//           b. or,reach tne
//5.   calc dtsep                        //calc exit spin-down delta time
//     if(tt>tse &&tt<tse+dtsep)         //shadow exit maneuver
//       calc and return yaw
//     if(tt>tse+dtsep)
//       step thru/interpolate to get either
//         a. yaw  -> return yaw
//         b. tshe                       //calc shadow exit maneuver end time
//6. return yawn
//}
```

3 Sample Results

The function, $GetRollPitchYaw(tle, t, attitude)$, computes the satellite roll, pitch and yaw angles. The input includes the orbit tle and the time, t. Below is a simple sample calling code, followed by a simple result. The result returned is given in units of radians.

code:

```
//GetRollPitchYaw Example
double attitude[3];
//Set up input
boost::posix_time::ptime t=                        //Set the time
  boost::posix_time::time_from_string("2014-Jan-01 12:00:16");
std::string tleLbl;
tleLbl="GPS BII-2  (PRN 13)    ";                  //Set tle Label
std::vector<std::string> tle;
tle.push_back(tleLbl);
tle.push_back(                                     //Set tle Line1
 "1 24876U 97035A   14014.34544831 -.00000019  00000-0  00000+0 0 7339");
tle.push_back(                                     //Set tle Line2
 "2 24876  56.0926 276.3741 0049820 126.6892 135.0293 2.00566940120765");
 cout<<"GetRollPitchYaw input tle:\n ";
 cout<<" "<<tle[0]<<"\n "<<tle[1]<<"\n "<<" "<<tle[2]<<"\n";
 cout<<"input time = "<<t<<" \n";

//run
BodyOrientationModel::GetRollPitchYaw(tle,t,attitude);

//output result
printf("GetRollPitchYaw output:\n");
printf(" roll= %.1lf  pitch= %.1lf  yaw= %.3lf  [rad]\n",
                attitude[0],attitude[1],attitude[2]);
```

result:

```
GetRollPitchYaw input tle:
 GPS BII-2  (PRN 13)
 1 24876U 97035A   14014.34544831 -.00000019  00000-0  00000+0 0 7339
 2 24876  56.0926 276.3741 0049820 126.6892 135.0293 2.00566940120765
input time = 2014-Jan-01 12:00:16

GetRollPitchYaw output:
 roll= 0.0  pitch= 0.0  yaw= -2.124  [rad]
```

In addition to the simple final result, more details of the computation can be generated by going into the source code routines for any function of interest in *BodyOrientationModel.cpp* and raising the "*iprt*" parameter that controls the amount of computational details written to the command window. A value of $iprt = 0$ (default) outputs the minimum result. Higher values (up to 3) write increasing detail, including such things as interim parameters and iteration convergence details.

4 Source Code Location:

The body orientation model DIORAMA functions are located in
/tle/src/BodyOrientationModel.cpp .
In addition, a yaw computation unit test checks, for two different satellite types and 5 different satellite locations around an orbit that exemplify various yaw maneuvers, that expected yaw angles are computed. The unit test code is located in:
/tle/testsrc/test_yaw.cpp .
Sample test_yaw output is presented in Table 2.

Table 2. Sample unit checks Varying μ of Yaw Angle Calculation

```
Start Report 0: nominal (before Noon maneuver)
 yaw=3.120 [rad] for type=iif prn=25030 beta=0.0218 mu=1.571 [rad]
 yaw=3.120 Expected value.

Start Report 1: Noon maneuver
 yaw=1.466 [rad] for type=iif prn=25030 beta=0.0218 mu=3.192 [rad]
 yaw=1.466 Expected value.

Start Report 2: nominal (after Noon maneuver)
 yaw=0.074 [rad] for type=iif prn=25030 beta=0.0218 mu=3.442 [rad]
 yaw=0.074 Expected value.

Start Report 3: Midnight maneuver
 yaw=0.734 [rad] for type=iif prn=25030 beta=0.0218 mu=6.278 [rad]
 yaw=0.734 Expected value.

Start Report 4: nominal (after Midnight maneuver)
 yaw=3.068 [rad] for type=iif prn=25030 beta=0.0218 mu=6.583 [rad]
 yaw=3.068 Expected value.

Start Report 0: nominal (before Noon maneuver)
 yaw=-0.022 [rad] for type=iia prn=25030 beta=0.0218 mu=1.571 [rad]
 yaw=-0.022 Expected value.

Start Report 1: Noon maneuver
 yaw=-1.605 [rad] for type=iia prn=25030 beta=0.0218 mu=3.192 [rad]
 yaw=-1.605 Expected value.

Start Report 2: nominal (after Noon maneuver)
 yaw=-3.068 [rad] for type=iia prn=25030 beta=0.0218 mu=3.442 [rad]
 yaw=-3.068 Expected value.

Start Report 3: Shadow Xing maneuver
 yaw=-0.248 [rad] for type=iia prn=25030 beta=0.0218 mu=6.278 [rad]
 yaw=-0.248 Expected value.

Start Report 4: nominal (after Post-Shadow maneuver)
 yaw=-0.074 [rad] for type=iia prn=25030 beta=0.0218 mu=6.583 [rad]
 yaw=-0.074 Expected value.
```

5 Summary

In summary, a satellite body orientation model has been added to DIORAMA that returns a satellite roll, pitch, and yaw attitude at a specified time. A two-line element (tle) representation of the satellite orbit is required, along with the time. Yaw orientation can affect geophysical applications including precise point-positioning [2] and sensor sensitivity.

The yaw attitude is controlled to maintain sensors and communication antennae pointed toward the earth and solar panels facing the sun while the satellite orbits the earth and, therefore, is constantly changing. Differing, complex satellite yaw angle maneuvers are a function of the satellite type, the orbital-plane β angle, the satellite position angle, μ, and the machine hardware maximum yaw rate. Each of these inputs is calculated during the orientation computation.

References

[1] J. Kouba, "A Simplified Yaw-Attitude Model for Eclipsing GPS Satellites", GPS Solut. (2009) 13:1-12.

[2] Yoaz E. Bar-Sever, "A New model for GPS Yaw Attitude", J. of Geodesy (1996) 70:714-723.

[3] Florian Dilssner, "GPS IIF-1 Antenna Phase Center and Attitude Modeling", Inside GNSS (Sept. 2010) p59-64.

[4] K.A. Werley, "Solar Position Model for use in DIORAMA", Los Alamos National Laboratory report, October 14, 2014, pp 1-4.

6 APPENDIX - GPS Satellite NORAD Numbers and Maximum Yaw Rates

Table A lists GPS satellite types, NORAD identification numbers, and machine (maximum) yaw rates. The data was accumulated mostly from various Tables on the internet. References of publications are provided for the machine yaw rate values. The machine yaw rates critically affect the actual yaw angle during periods of special maneuvers. Type *ii* and *iia* satellites have unique machine (maximum) yaw rates for each satellite. Type *iif* satellites feature a different measured machine (maximum) yaw rate value for the noon and the midnight maneuver [3]. Following the direction of Ben Norman, type iii satellites are treated (assumed) to follow the same yaw angle model behavior as type iif satellites.

Table A. GPS Satellite Type and Machine_Yaw_Rate vs. NORAD Number

Name	type	svn	prn	NORAD#	Launch_date	Period (min)	Machine_max_yaw rate (degr/sec)
NAVSTAR 72 (USA 258)	iif	69	3	40294	10/29/2014	728.7	0.11/0.06 [3]
NAVSTAR 71 (USA 256)	iif	68	9	40105	08/02/2014	718	0.11/0.06 [3]
NAVSTAR 70 (USA 251)	iif	67	6	39741	05/17/2014	718	0.11/0.06 [3]
NAVSTAR 69 (USA 248)	iif	64	30	39533	02/21/2014	718	0.11/0.06 [3]
NAVSTAR 68 (USA 242)	iif	66	27	39166	05/15/2013	718	0.11/0.06 [3]
NAVSTAR 67 (USA 239)	iif	65	24	38833	10/04/2012	718	0.11/0.06 [3]
NAVSTAR 66 (USA 232)	iif	63	1	37753	07/16/2011	718	0.11/0.06 [3]
NAVSTAR 65 (USA 213)	iif	62	25	36585	05/28/2010	718	0.11/0.06 [3]
NAVSTAR 64 (USA 206)	iirm	50	5	35752	08/17/2009	718	0.2 [1]
NAVSTAR 63 (USA 203)	iirm	49	m	34661	03/24/2009	718	0.2 [1]
NAVSTAR 62 (USA 201)	iirm	48	7	32711	03/15/2008	717.9	0.2 [1]
NAVSTAR 61 (USA 199)	iirm	57	29	32384	12/20/2007	717.9	0.2 [1]
NAVSTAR 60 (USA 196)	iirm	55	15	32260	10/17/2007	718	0.2 [1]
NAVSTAR 59 (USA 192)	iirm	58	12	29601	11/17/2006	718	0.2 [1]
NAVSTAR 58 (USA 190)	iirm	52	31	29486	09/25/2006	718	0.2 [1]
NAVSTAR 57 (USA 183)	iirm	53	17	28874	09/26/2005	718	0.2 [1]
NAVSTAR 56 (USA 180)	iir	61	2	28474	11/06/2004	718	0.2 [1]
NAVSTAR 55 (USA 178)	iir	60	23	28361	06/23/2004	718	0.2 [1]
NAVSTAR 54 (USA 177)	iir	59	19	28190	03/20/2004	718	0.2 [1]
NAVSTAR 53 (USA 175)	iir	47	22	28129	12/21/2003	718	0.2 [1]
NAVSTAR 52 (USA 168)	iir	45	21	27704	03/31/2003	718	0.2 [1]
NAVSTAR 51 (USA 166)	iir	56	16	27663	01/29/2003	718	0.2 [1]
NAVSTAR 50 (USA 156)	iir	54	18	26690	01/30/2001	718	0.2 [1]
NAVSTAR 49 (USA 154)	iir	41	14	26605	11/10/2000	718	0.2 [1]
NAVSTAR 48 (USA 151)	iir	44	28	26407	07/16/2000	718	0.2 [1]
NAVSTAR 47 (USA 150)	iir	51	20	26360	05/11/2000	718	0.2 [1]
NAVSTAR 46 (USA 145)	iir	46	11	25933	10/07/1999	718	0.2 [1]
NAVSTAR 44 (USA 135)	iia	38	8	25030	11/06/1997	717.4	0.103 [1]
NAVSTAR 43 (USA 132)	iir	43	13	24876	07/23/1997	718.9	0.2 [1]
NAVSTAR 39 (USA 128)	iia	30	30	24320	09/12/1996	772.1	0.119 [1]
NAVSTAR 38 (USA 126)	iia	40	10	23953	07/16/1996	718	0.098 [1]
NAVSTAR 37 (USA 117)	iia	33	3	23833	03/28/1996	739.9	0.123 [1]
NAVSTAR 36 (USA 100)	iia	36	6	23027	03/10/1994	718	0.127 [1]
NAVSTAR 35 (USA 96)	iia	34	4	22877	10/26/1993	718	0.123 [1]
NAVSTAR 34 (USA 94)	iia	35	m	22779	08/30/1993	718	0.122 [1]
NAVSTAR 33 (USA 92)	iia	39	9	22700	06/26/1993	718	0.128 [1]
NAVSTAR 32 (USA 91)	iia	37	7	22657	05/13/1993	717.9	0.128 [1]
NAVSTAR 31 (USA 90)	iia	31	31	22581	03/30/1993	762.1	
NAVSTAR 30 (USA 88)	iia	22	22	22446	02/03/1993	765.6	
NAVSTAR 29 (USA 87)	iia	29	29	22275	12/18/1992	764.9	0.127 [1]
NAVSTAR 28 (USA 85)	iia	32	m	22231	11/22/1992	718	0.123 [1]
NAVSTAR 27 (USA 84)	iia	27	−1	22108	09/09/1992	717.9	0.120 [1]
NAVSTAR 26 (USA 83)	iia	26	26	22014	07/07/1992	718	0.123 [1]
NAVSTAR 25 (USA 80)	iia	28	28	21930	04/10/1992	767.3	
NAVSTAR 24 (USA 79)	iia	25	25	21890	02/23/1992	750.7	0.101 [1]
NAVSTAR 23 (USA 71)	iia	24	24	21552	07/04/1991	750.6	0.112 [1]
NAVSTAR 22 (USA 66)	iia	23	32	20959	11/26/1990	717.9	0.114 [1]
USA 64	ii	15	−1	20830			0.134 [1]

m=multiple prn values — noon/midnight