

Velocity and Acceleration of NavIC Satellites using Broadcast Ephemeris

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Abstract

The current manuscript describes a methodology to derive velocity and acceleration of NavIC satellites from the broadcast ephemeris. A fourth-order central differencing formula is used to derive NavIC satellites' Earth-Centred-Earth-Fixed (ECEF) velocity from the ECEF positions that are calculated using the standard IRNSS-SIS-ICD algorithm. The proposed methodology is quite simpler and straight forward than the conventional rotation matrix method and therefore it can be a very good alternative to the existing approaches. The same differencing formula has been further implemented to derive the ECEF acceleration from the ECEF velocities. Results obtained demonstrated that the satellites' ECEF velocity can be approximated upto an accuracy of 0.6 mm/s while the ECEF acceleration can be of the further accuracy of within 0.06 mm/sec² in each axis.

Keywords- Velocity, Acceleration, Broadcast ephemeris, Earth-Centred-Earth-Fixed, NavIC.

1. Introduction

Indian Space Research Organization (ISRO) is in the process of deploying an independent regional navigational system with an operational name NavIC (Navigation with Indian constellation) (Gogoi et al., 2017). The present constellation of NavIC comprises of seven satellites, 3 GEO satellites located at 32.5° E, 83° E and 129.5° E and 4 GSO satellites with their longitude crossings 55° E and 111.75° E (two in each plane) (IRNSS SIS ICD, 2011). All these seven satellites are fully operational and currently NavIC provides a position accuracy better than 20 meters over India and a region extending about 1500 km around India. The navigation system of NavIC is generally known as Indian Regional Navigation Satellite System (IRNSS). IRNSS User segment comprises of single and dual frequency navigation users operating on L5 and S frequencies.

The objective of the current work is to provide a methodology wherein NavIC can be utilized for precise velocity and acceleration determination of a number of applications like automobile brake system testing, athlete monitoring, airborne gravimetry (Yun and Zheren, 2003), moving base gravimetry (Jekeli, 2016) and other varied applications. The velocities and accelerations of atleast 4 IRNSS satellites must be determined and taken as known values to find the velocity and acceleration of a NavIC user.

In this work, firstly we calculate the satellite Earth-Centred-Earth-Fixed (ECEF) position with the help of orbital parameters as obtained from broadcast ephemeris and according to the algorithm mentioned in IRNSS SIS ICD (IRNSS SIS ICD, 2011). Then we propose a simple methodology which uses the fourth-order central difference of a Taylor series approximations of the satellite

ECEF positions to derive the satellites ECEF velocity. Similarly, we utilize these ECEF velocities and the fourth-order central difference formula to derive the satellites ECEF acceleration.

To validate the results, we have done a comparison exercise of our results with the velocities and accelerations derived from precise ephemeris and it is found to be in the excellent match. It has been observed that the ECEF velocity and ECEF acceleration using broadcast ephemeris and with the current methodology agrees very well with the precise ones within an accuracy of ± 0.6 mm/s for velocity and ± 0.06 mm/s² for acceleration respectively. The paper has been arranged in five sections. Section 2 describes the IRNSS broadcast ephemeris (navigation message) and navigation file format, Section 3 the fourth-order methodology, Section 4 the results and analysis and finally Section 5 summarizes the whole work.

2. IRNSS Broadcast Ephemeris

For ease of convenience, the IRNSS broadcast navigation messages are converted into ASCII type and put into the form of standard RINEX (Receiver Independent Exchange) file format as RINEX navigation file. These files consist of two sections, namely, a header section and a data section. The header section consists of global information of the file and it is usually placed at the beginning of the RINEX file. It contains header labels in columns 61-80 for each of the lines in the header section. These labels are mandatory and they must appear exactly as shown in Fig. 1.

The data section of IRNSS RINEX navigation file consists of the broadcast navigation parameters. The first row of each navigation data contains the satellite number, current epoch (year, month, day, hour, minutes and seconds) and the satellite clock information (bias, drift and drift rate of the clock) followed by the navigation parameters which include issue of data ephemeris, sine and cosine corrections to orbital radius, mean motion difference, mean anomaly, sine and cosine corrections to argument of latitude, eccentricity, semi-major axis of orbit, time of ephemeris, sine and cosine corrections to angle of inclination etc. as shown in Fig. 1.

2.11 NAVIGATION DATA					RINEX
VERSION / TYPE					
XXRINEXN V2	SNG/MDA/ISAC	Thu Jul 6 03:43:48 2017	UTC	PGM /	
RUN BY / DATE					
NavIC BROADCAST EPHEMERIS FILE 2.11 FORMAT					COMMENT
SNG - SPACE NAVIGATION GROUP					COMMENT
MDA - MISSION DEVELOPMENT AREA					COMMENT
ISAC - ISRO SATELLITE CENTRE					COMMENT
					END OF HEADER
PRNID	Yr Mo Day Hr Min Sec	A ₀ A ₁ A ₂			
IODE	C_{rs}	Δn	M_0	<u>BRORB-1</u>	
C_{uc}	e	C_{us}	\sqrt{a}	<u>BRORB-2</u>	
t_{oe}	C_{ic}	Ω_0	C_{is}	<u>BRORB-3</u>	
i_0	C_{rc}	ω	Ω_{dot}	<u>BRORB-4</u>	
i_{dot}	Codes on S signal	IRNSS Week	S data flag	<u>BRORB-5</u>	
SV accuracy	SV Health	TGD	IODC	<u>BRORB-6</u>	
Msg Trans. time	Fit Interval	Spare	Spare	<u>BRORB-7</u>	

Fig. 1. Format for RINEX navigation data of IRNSS

In Fig. 1, we have shown the RINEX navigation file format for broadcast ephemeris of IRNSS. This format describes the orbital parameters in seven broadcast orbits and the definitions for each of the acronyms used has been represented in Table 1.

Table 1. Ephemeris data definitions

IODE	Issue of Data ephemeris
C_{rs}	Sine correction to orbital radius
Δn	Mean motion difference from computed value
M_0	Mean anomaly at reference time
C_{uc}	Cosine correction to argument of latitude
e	eccentricity
C_{us}	Sine correction to argument of latitude
\sqrt{a}	Square root of semi-major axis
t_{oe}	Time of ephemeris
C_{ic}	Cosine correction to angle of inclination
Q_0	Right ascension of ascending node
C_{is}	Sine correction to angle of inclination
i_0	Angle of inclination
C_{rc}	Cosine correction to orbital radius
ω	Argument of perigee
Q_{dot}	Rate of right ascension
i_{dot}	Rate of inclination angle

Fig. 2 shows a typical example of IRNSS navigation message in RINEX format (broadcast ephemeris) for 17 February 2017.

3. Fourth-Order Central Differencing Formula

To derive the NavIC satellites velocities and acceleration we first obtain the satellites ECEF with the position algorithm as documented in IRNSS SIS ICD (IRNSS SIS ICD, 2011). Next to derive the velocity and acceleration we used the central differencing techniques (Whittaker and Robinson, 1967). This technique was first used by Whittaker and Robinson in 1967 where they used Taylor series approximations about a fixed point. Then by using Taylor's Remainder Theorem and the number of approximations, the desired level of accuracy can be achieved with the help of some simple algebraic calculations. In this work, we have used the following fourth-order central difference formula

$$f_i' = \frac{-f_{i+2} + 8f_{i+1} - 8f_{i-1} + f_{i-2}}{12h}$$

Here f_i represents the fundamental quantity and f_i' denotes the 4th order approximation of f_i with respect to time and h is the time-step. Thus, when we chose f as position, f' gives us velocity and choosing f as velocity yields f'' as acceleration.

2.11	N: IRNSS NAV DATA SNG/ISAC	11-FEB-2017		RINEX VERSION / TYPE PGM / RUN BY / DATE COMMENT	
2.0489096642E-08	2.1606683731E-07	-2.3841857910E-06	-7.5101852417E-06	ION ALPHA	
0.0000000000E+00	1.4417920000E+06	-8.3230720000E+06	8.3230720000E+06	ION BETA	
0.0	0.0	0	0	DELTA-UTC: A0,A1,T,W	
18				LEAP SECONDS	
				END OF HEADER	
03 17 02 10 23 50 24.000000	-4.5818742365E-04	4.3996806198E-11	0.0000000000E+00		
1.6000000000E+02	-6.9043750000E+02	1.2236223974E-08	-7.0672335658E-01		
-2.2180378437E-05	2.1432776703E-03	-2.3182481527E-05	6.4934056263E+03		
5.1782400000E+05	-3.0547380447E-07	2.0668285144E+00	-7.6740980148E-07		
5.6521956835E-02	7.0456250000E+02	1.5091639919E-01	-1.1333329222E-08		
-5.0002082787E-11	0.0000000000E+00	9.1100000000E+02	0.0000000000E+00		
0.0000000000E+00	0.0000000000E+00	-1.3969838619E-09	1.6000000000E+02		
5.1782400000E+05	9.0000000000E+02				
02 17 02 11 00 00 0.000000	3.4309783950E-04	-4.7862158681E-11	0.0000000000E+00		
0.0000000000E+00	-4.5275000000E+02	3.3329959755E-09	1.4221280216E+00		
-1.5050172806E-05	1.6657958040E-03	2.6334077120E-05	6.4934733601E+03		
5.1840000000E+05	3.2037496567E-07	2.8217994841E+00	-6.7055225372E-08		
5.1168683152E-01	-7.2431250000E+02	3.1028220753E+00	-3.1101295494E-09		
-1.0682587830E-09	0.0000000000E+00	9.1100000000E+02	0.0000000000E+00		
0.0000000000E+00	0.0000000000E+00	-1.8626451492E-09	0.0000000000E+00		
5.1840000000E+05	7.2000000000E+03				
04 17 02 11 00 00 0.000000	1.5825964510E-05	-3.2287061913E-11	0.0000000000E+00		
0.0000000000E+00	-3.6068750000E+02	3.3572827014E-09	2.3872547353E+00		
-1.1987984180E-05	1.7797080800E-03	2.3547559977E-05	6.4932443275E+03		
5.1840000000E+05	-2.9802322388E-08	2.8242095188E+00	1.6391277313E-07		
5.1151645277E-01	-6.3568750000E+02	3.1248329169E+00	-2.9044066945E-09		
-8.5539277340E-10	0.0000000000E+00	9.1100000000E+02	0.0000000000E+00		
0.0000000000E+00	0.0000000000E+00	-1.3969838619E-09	0.0000000000E+00		
5.1840000000E+05	7.2000000000E+03				
05 17 02 11 00 00 0.000000	1.3195164502E-04	-3.8994585339E-11	0.0000000000E+00		
0.0000000000E+00	-7.5612500000E+02	2.6272522927E-09	-7.8000768478E-01		
-2.5104731321E-05	2.1042987937E-03	1.8674880266E-05	6.4933745937E+03		
5.1840000000E+05	7.0780515671E-08	-3.1984552290E-01	-1.1175870895E-07		
4.9962444437E-01	-4.8931250000E+02	-3.1287797017E+00	-2.3429547363E-09		
-8.5003540739E-11	0.0000000000E+00	9.1100000000E+02	0.0000000000E+00		
0.0000000000E+00	0.0000000000E+00	-4.6566128731E-10	0.0000000000E+00		
5.1840000000E+05	7.2000000000E+03				
06 17 02 11 00 00 0.000000	-6.0012144968E-04	-5.0704329624E-11	0.0000000000E+00		
0.0000000000E+00	-1.0026250000E+03	1.3221979320E-08	1.6348792528E+00		
-3.2577663660E-05	1.7720843898E-03	-1.0143965483E-05	6.4933664341E+03		
5.1840000000E+05	7.8231096268E-08	2.3169845494E+00	1.4156103134E-07		
7.6667572026E-02	3.1125000000E+02	3.0016378498E+00	-1.2340514032E-08		
-5.2252176513E-10	0.0000000000E+00	9.1100000000E+02	0.0000000000E+00		
0.0000000000E+00	0.0000000000E+00	-1.8626451492E-09	0.0000000000E+00		
5.1840000000E+05	7.2000000000E+03				
07 17 02 11 00 00 0.000000	5.5515673012E-04	-7.4010131357E-11	0.0000000000E+00		
0.0000000000E+00	-8.4981250000E+02	1.0677587622E-08	-4.5058155381E-01		
-2.7894973755E-05	3.4211482853E-04	-6.1243772507E-06	6.4932807846E+03		
5.1840000000E+05	-1.1548399925E-07	2.3392642578E+00	-8.9406967163E-08		
7.7969283848E-02	1.7875000000E+02	4.7476742397E-01	-9.5418260268E-09		
-3.6715815075E-10	0.0000000000E+00	9.1100000000E+02	0.0000000000E+00		
0.0000000000E+00	0.0000000000E+00	-1.3969838619E-09	0.0000000000E+00		
5.1840000000E+05	7.2000000000E+03				
03 17 02 11 00 05 36.000000	-4.5814784244E-04	4.3087311496E-11	0.0000000000E+00		
1.6100000000E+02	-6.6856250000E+02	1.2183364629E-08	-6.4121915735E-01		
-2.1528452635E-05	2.1408441244E-03	-2.2869557142E-05	6.4933968544E+03		
5.1873600000E+05	-1.5273690224E-07	2.0668172660E+00	-7.3760747910E-07		
5.6521946595E-02	6.9518750000E+02	1.5192843129E-01	-1.1246182734E-08		
-6.9645758168E-11	0.0000000000E+00	9.1100000000E+02	0.0000000000E+00		
0.0000000000E+00	0.0000000000E+00	-1.3969838619E-09	1.6100000000E+02		
5.1873600000E+05	9.0000000000E+02				
03 17 02 11 00 20 48.000000	-4.5810732990E-04	4.3996806198E-11	0.0000000000E+00		
1.6200000000E+02	-6.4862500000E+02	1.2353371710E-08	-5.7529567117E-01		
-2.0943582058E-05	2.1392141934E-03	-2.2474676371E-05	6.4933919621E+03		
5.1964800000E+05	-3.3527612686E-08	2.0668081096E+00	-6.5565109253E-07		
5.6521738860E-02	6.8281250000E+02	1.5251924538E-01	-1.1380474042E-08		
-9.2503853157E-11	0.0000000000E+00	9.1100000000E+02	0.0000000000E+00		
0.0000000000E+00	0.0000000000E+00	-1.3969838619E-09	1.6200000000E+02		
5.1964800000E+05	9.0000000000E+02				

Fig. 2. IRNSS navigation data in RINEX format

4. Results and Analysis

To carry out analysis we chose the IRNSS satellite IRNSS-1F and derive its velocity and acceleration for the Day of Year (DOY) 138 of 2017 i.e. 18-05-2017. Our results are shown in Fig. 3-6. Fig. 3 and Fig. 4 show side-by-side plots of velocity and acceleration in comparison with the velocity and acceleration obtained from precise ephemeris (running time of 120 seconds). One can see an excellent match between the two results in both the cases.

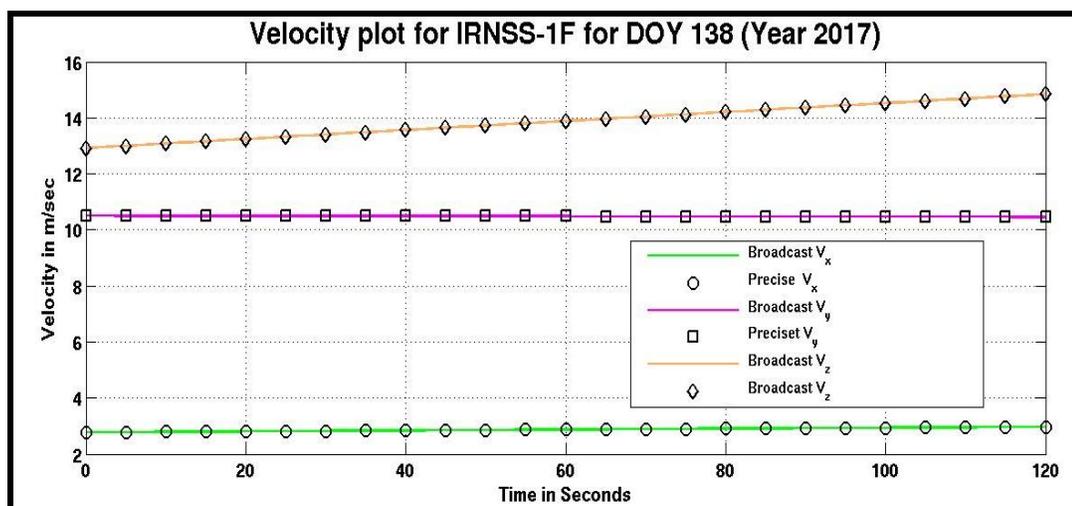


Fig. 3. Velocity comparison of IRNSS-1F for DOY 138 (Year 2017): Precise vs Broadcast

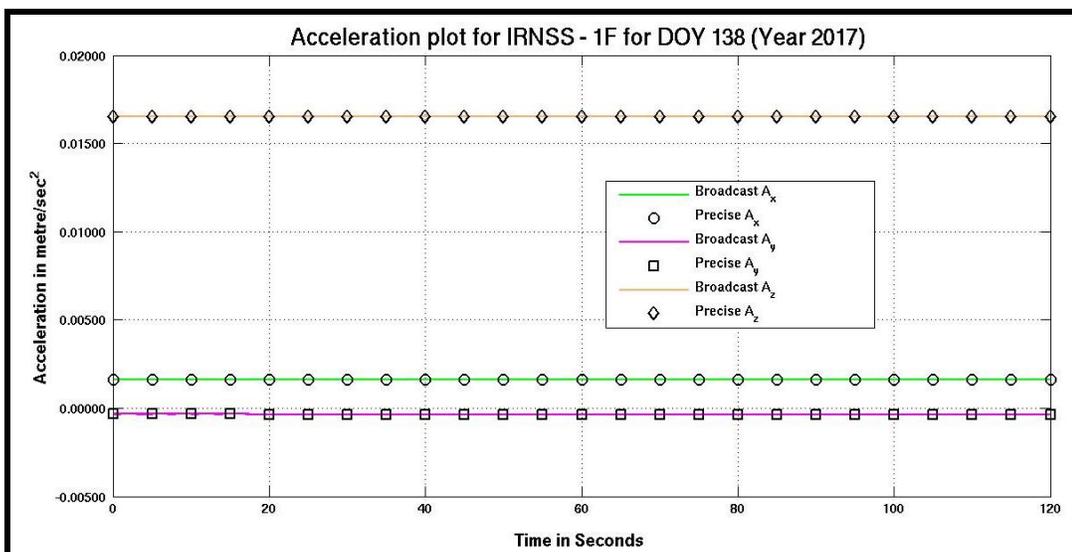


Fig. 4. Acceleration comparison of IRNSS-1F for DOY 138 (Year 2017): Precise vs Broadcast

In Fig. 5, we have shown the residuals of the 4th-order velocity to the velocity from precise ephemeris and in Fig. 6 we have shown the residuals of the 4th-order acceleration to the acceleration from the precise ephemeris. From the plot, one can clearly see an accuracy of 0.6 mm/s for the ECEF velocity and an accuracy 0.06 mm/s² for the ECEF acceleration.

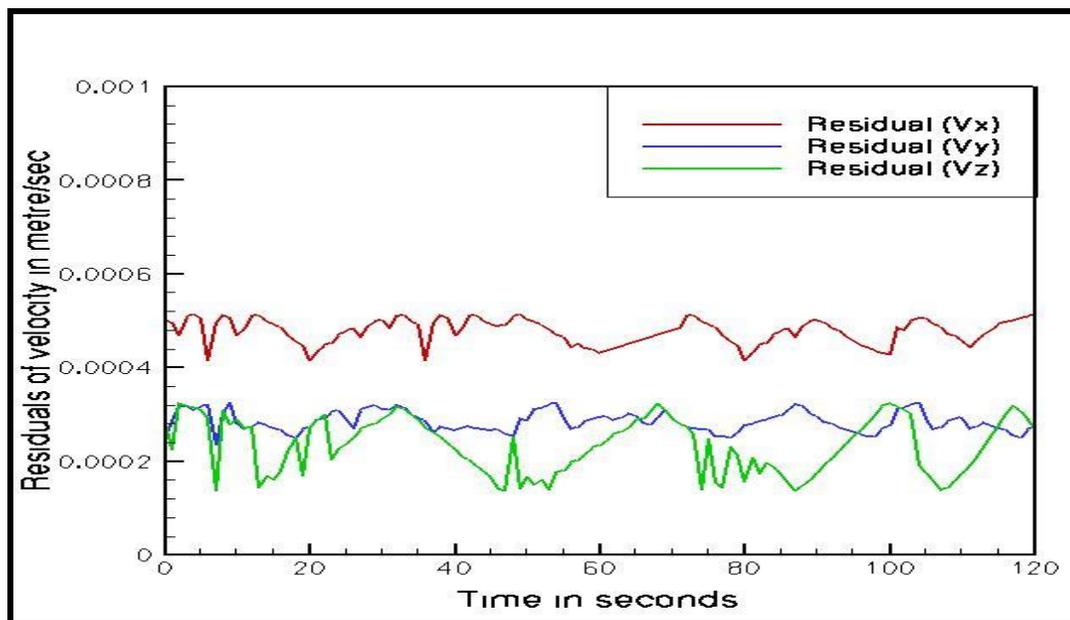


Fig. 5. Residual of 4th order derived velocity from precise one for Day of Year (DOY:138), starting from 18:00:00 to 18:02:00 for IRNSS-1F

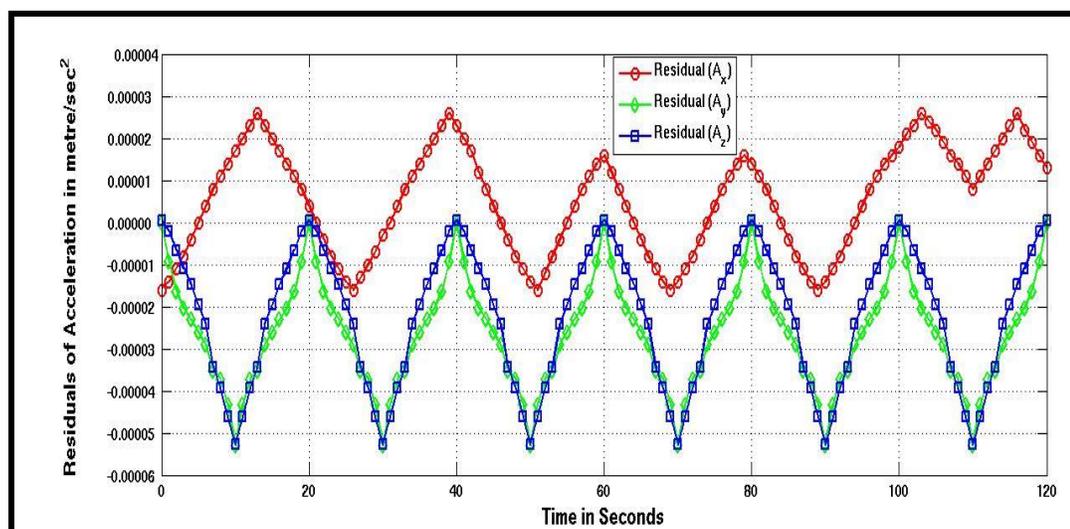


Fig. 6. Residual of 4th order derived acceleration from precise one for Day of Year (DOY:138), starting from 18:00:00 to 18:02:00 for IRNSS-1F

5. Conclusion

The work in this manuscript presented a simple methodology of deriving satellite velocity and acceleration from the broadcast ephemeris. This has the scope of finding NavIC user velocity and acceleration as well as in many important practical applications. The current methodology on compared with the results from precise ephemeris showed very excellent and promising results. Currently the methodology has been implemented for only one IRNSS satellites. Efforts are going on to test it for the full NavIC constellation and to implement it in real time mode.

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