Estimation of PW-Sat satellite orbit based on Doppler effect

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ABSTRACT

PW-Sat satellite has been launched into the orbit together with eight other small satellites. After the launch and separation they were occupying very close positions (what has been indicated by radar observations), so it was impossible to determine which object was PW-Sat. This article describes how the exact position of satellite has been determined by means of precision signal reception and employing Doppler shift calculations.

Keywords: satellite, cubesat, orbit, Doppler effect, PW-Sat

1. INTRODUCTION

The PW-Sat satellite [1] has been launched into the orbit on 13th February 2012 from the Kourou launch site in French Guiana onboard of Vega1 rocket [2]. PW-sat is 1U cubesat type satellite (10x10x10 cm, 1 kg) launched together with other six cubesats and two bigger satellites. This satellite has been built by students of Warsaw University of Technology with support of Space Research Center of Polish Academy of Sciences.

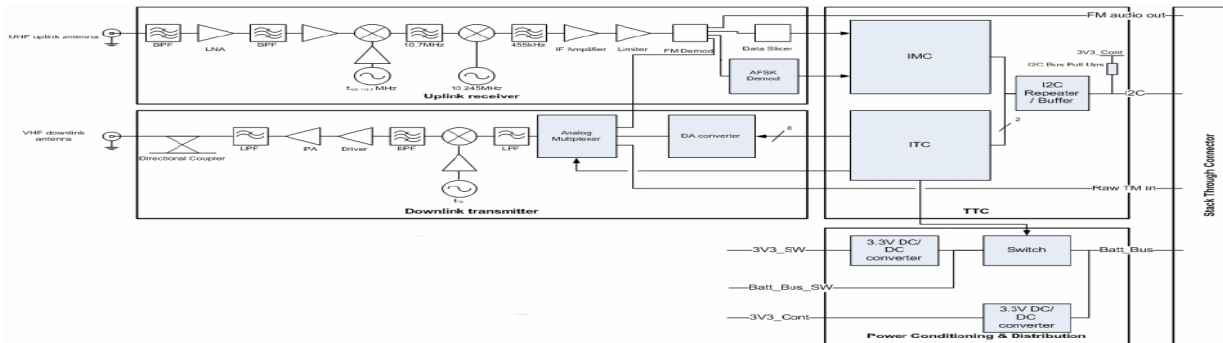## 2. COMUNICATION SYSTEM DESIGN

Figure 1. Communication module block diagram of PW-Sat satellite.

The communication system of satellite utilizes ISIS_TRXUV module [3]. The receiver circuit [Figure 1] is composed of double conversion superheterodine and FM demodulator. The next steps are AFSK demodulator and microcontroller. The transmitter includes single conversion and power amplifier. The source feed for transmitter is microcontroller and DAC which generate BPSK modulated signals. The other input for transmitter (when satellite is in voice repeater mode) is an audio signal from FM demodulator which fed to transmitter frequency mixer creates DSB signal. Additionally the transmitter module is used for CW modulation when satellite is in beacon mode. The assumed parameters of communication module are:

- Up Link - UHF 435.020 MHz AFSK 1200 AX.25
- Up Link - UHF 435.020 MHz FM Voice
- Down Link - VHF 145.900 MHz BPSK 1200 AX.25 (200 mW)
- Down Link - VHF 145.900 MHz DSB Voice (repeter 200 mW)
- Beacon - VHF 145.900 MHz CW (200 mW)

3. MEASUREMENT OF DOWNLINK FREQUENCY AND ORBIT ESTIMATION OF PW-SAT SATELLITE

PW-sat has been launched together with other eight satellites. By means of NORAD radar observations the positions of all objects have been determined [5] but distinguishing which position is for which particular satellite is a task for each operation team. The on-orbit distribution of objects of interest as for 2012-03-30 is presented on [Figure 2].
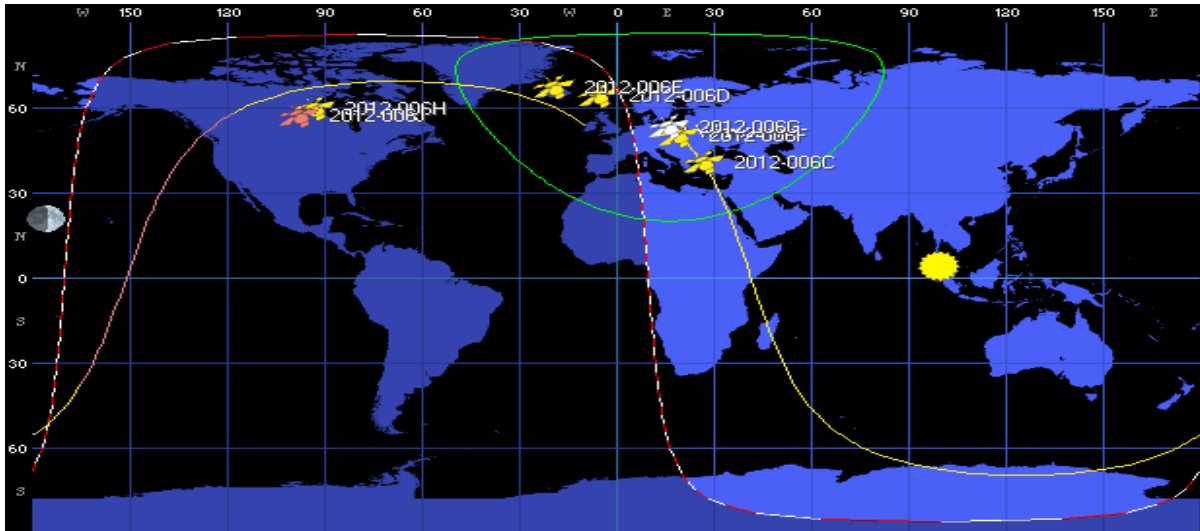

Figure 2. On-orbit distribution of objects detected by NORAD on 2012-03-30.

The objects not recognized are: 2012-006C, 2012-006D, 2012-006E, 2012-006F, 2012-006G, 2012-006H, 2012-006J. One of the is PW-sat. The initial assumptions (based on the order of satellite separation from the stage of the rocket) were that this was object 2012-006G but it was to be confirmed by means of precise research.

Figure 3. Structure of measurement system used for precise frequency estimation of PW-Sat.
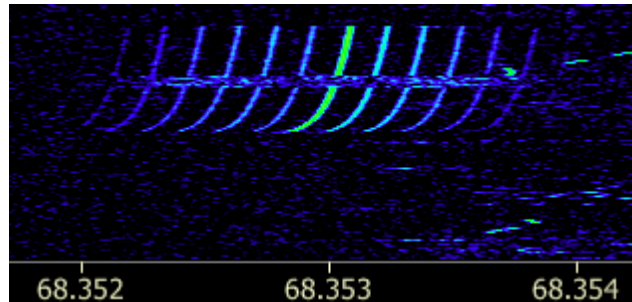

Figure 4. Spectrum of PW-Sat signal received by means of measurement system presented in Figure 3.

In the period form 2012-03-26 to 2012-03-30 the series of subsequent signal reception has been performed. For the reception the SQ5FNQ ground station (located in Warsaw) was used. This station consists of [Figure 3]:

- Set of directional antennas mounted on Az-El rotator
- Yaesu FT-847 satellite transceiver with 45 MHz IF output
- Yaesu FT-817 transceiver working as IF frequency shifter from 45 MHz to 70 MHz
- FunCube dongle receiver (SDR receiver working in the range 50-1700 MHz) used as spectrum analyzer for signal from FT-847 fed through FT-817
- Refference signal generator HAMEG 8135 (frequency stabilization of 1E-8 Hz)
- PC computer with time synchronization from Internet NTP

During five days of measurements and seven communication windows there have been received 30 signals from PW-sat [Figure 4]. The results are presented in [Table 1]. It is worth to notice that satellite works in undetermined mode and

transmits signals rarely. The estimation of current frequency of satellite and its orbit by means of Doppler effect is best realized by turning continuous downlink transmission and long-term frequency measurements. Unfortunately, the two way communication with satellite hasn't been established yet so changing the satellite transceiver mode was not possible. The frequency indicated by students was to be 145.900 MHz or 145.902 MHz.

Table 1. PW-Sat downlink frequency measurements.

| No.	Window	Data Time (UTC)	PW_SAT FRQ [Hz]	T	dT	dFRQ	dFRQ/dT
1	1	2012-03-26 5:57:05	145908158	0	0:00:00	0	0
2	1	2012-03-26 5:57:52	145907355	0:00:47	0:00:47	-803	-17,0851
3	1	2012-03-26 5:58:48	145906452	0:01:43	0:00:56	-903	-16,125
4	1	2012-03-26 5:59:00	145906252	0:01:55	0:00:12	-200	-16,6667
5	1	2012-03-26 5:59:30	145905750	0:02:25	0:00:30	-502	-16,7333
6	2	2012-03-26 7:35:37	145909060	0:00:00	0:00:00	0	0
7	2	2012-03-26 7:35:50	145909010	0:00:13	0:00:13	-50	-3,84615
8	2	2012-03-26 7:36:20	145908910	0:00:43	0:00:30	-100	-3,33333
9	3	2012-03-27 5:53:37	145904446	0:00:00	0:00:00	0	0
10	3	2012-03-27 5:54:20	145904146	0:00:43	0:00:43	-300	-6,97674
11	3	2012-03-27 5:55:53	145903892	0:02:16	0:01:33	-254	-7,69697
12	4	2012-03-28 5:52:30	145904146	0:00:00	0:00:00	0	0
13	4	2012-03-28 5:53:02	145904045	0:00:32	0:00:32	-101	-3,15625
14	4	2012-03-28 5:53:58	145903945	0:01:28	0:00:56	-100	-1,78571
15	5	2012-03-28 7:26:35	145906753	0:00:00	0:00:00	0	0
16	5	2012-03-28 7:27:18	145906252	0:00:43	0:00:43	-501	-11,6512
17	5	2012-03-28 7:28:15	145905801	0:01:40	0:00:57	-451	-7,91228
18	5	2012-03-28 7:28:26	145905650	0:01:51	0:00:11	-151	-13,7273
19	6	2012-03-30 5:18:36	145909096	0:00:00	0:00:00	0	0
20	6	2012-03-30 5:19:32	145908960	0:00:56	0:00:56	-136	-2,42857
21	6	2012-03-30 5:19:46	145908896	0:01:10	0:00:14	-64	-4,57143
22	6	2012-03-30 5:20:10	145908864	0:01:34	0:00:24	-32	-1,33333
23	6	2012-03-30 5:34:25	145903632	0:15:49	0:14:15	-5232	-348,8
24	6	2012-03-30 5:35:13	145903512	0:16:37	0:00:48	-120	-2,5
25	7	2012-03-30 7:12:34	145904704	0:00:00	0:00:00	0	0
26	7	2012-03-30 7:13:28	145904368	0:00:54	0:00:54	-336	-6,22222
27	7	2012-03-30 7:13:41	145904296	0:01:07	0:00:13	-72	-5,53846
28	7	2012-03-30 7:14:11	145904120	0:01:37	0:00:30	-176	-5,86667
29	7	2012-03-30 7:14:35	145904032	0:02:01	0:00:24	-88	-3,66667
30	7	2012-03-30 7:15:04	145903936	0:02:30	0:00:29	-96	-3,31034
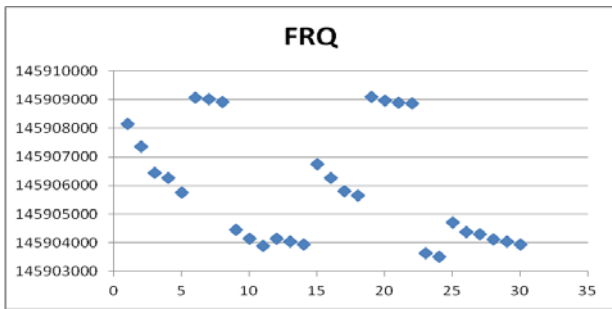
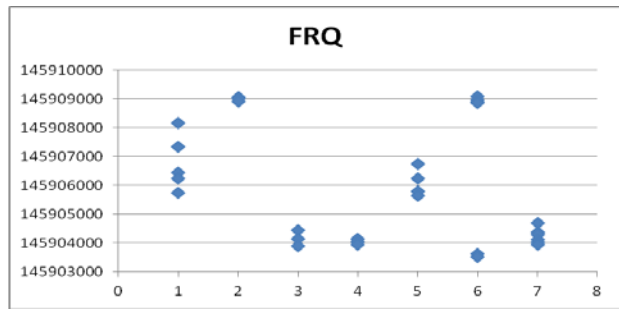Figure 5. Satellite frequency as a function of received packet number.

Figure 6. Satellite frequency as a function of communication window.

During series of signals reception it was found that signals was in the range from MIN = 145903512 Hz to MAX = 145909096 Hz [Table 1, Figure 5, Figure 6]. The mean value of radio frequency of series of received signals was 145905948 Hz while the mean value from MIN and MAX values was MID = 145906304 Hz. It was temporary assumed that the PW-Sat frequency is 145906000 Hz.

Based on this estimation and using Orbitron software [4] frequency was determined taking into account Doppler effect (relative to SQ5FNQ ground station) for each of unrecognized objects for communications windows number 6 and 7. The summary of simulations is shown in [Table 2].

Table 2. Summary of frequency simulations for all launched objects.

No.	Window	Data Time (UTC)	PW_SAT FRQ [Hz]	C FRQ [Hz]	D FRQ [Hz]	E FRQ [Hz]	F FRQ [Hz]	G FRQ [Hz]	H FRQ [Hz]	J FRQ [Hz]
19	6	2012-03-30 5:18:36	145909096	145907717	**145908890**	**145908878**	145908659	**145908750**	145908567	145908512
20	6	2012-03-30 5:19:32	145908960	145907123	**145908885**	**145908886**	145908531	**145908666**	145908615	145908564
21	6	2012-03-30 5:19:46	145908896	145906955	**145908883**	**145908887**	145908491	**145908640**	145908627	145908576
22	6	2012-03-30 5:20:10	145908864	145906613	**145908877**	**145908888**	145908407	**145908586**	145908647	145908598
23	6	2012-03-30 5:34:25	145903632	**145903340**	**145903765**	145904511	145903305	145903316	145908738	145908793
24	6	2012-03-30 5:35:13	145903512	**145903357**	**145903608**	145904131	145903306	145903308	145908672	145908748
25	7	2012-03-30 7:12:34	145904704	145903802	145906750	145907425	145904405	**145904704**	145908552	145908572
26	7	2012-03-30 7:13:28	145904368	145903726	145906368	145907128	145904201	**145904445**	145908519	145908549
27	7	2012-03-30 7:13:41	145904296	145903711	145906274	145907050	145904158	**145904390**	145908509	145908542
28	7	2012-03-30 7:14:11	145904120	145903679	145906045	145906855	**145904066**	145904270	**145908484**	**145908524**
29	7	2012-03-30 7:14:35	145904032	145903658	145905868	145906695	**145904003**	145904187	**145908461**	**145908507**
30	7	2012-03-30 7:15:04	145903936	145903638	145905658	145906494	**145903935**	145904098	**145908430**	**145908483**

The bold font in the above table designates signals which should be impossible to receive because given object in this moment is below radio horizon. The bolded and underlined font designates objects which in given moment were closest to the signal of PW-sat. [Table 3] shows similar summary but the calculated frequency shift relative to PW-sat frequency is presented.

Table 3. Summary of frequency shifts simulations for all launched objects.

No.	Window	Data Time (UTC)	PW_SAT FRQ [Hz]	C dFRQ [Hz]	D dFRQ [Hz]	E dFRQ [Hz]	F dFRQ [Hz]	G dFRQ [Hz]	H dFRQ [Hz]	J dFRQ [Hz]
19	6	2012-03-30 5:18:36	145909096	1379	**206**	218	437	**346**	529	584
20	6	2012-03-30 5:19:32	145908960	1837	75	**74**	429	**294**	345	396
21	6	2012-03-30 5:19:46	145908896	1941	13	**9**	405	**256**	269	320
22	6	2012-03-30 5:20:10	145908864	2251	**-13**	-24	457	**278**	217	266
23	6	2012-03-30 5:34:25	145903632	292	**-133**	-879	327	316	-5106	-5161
24	6	2012-03-30 5:35:13	145903512	155	**-96**	-619	206	204	-5160	-5236
25	7	2012-03-30 7:12:34	145904704	902	-2046	-2721	299	**0**	-3848	-3868
26	7	2012-03-30 7:13:28	145904368	642	-2000	-2760	167	**-77**	-4151	-4181
27	7	2012-03-30 7:13:41	145904296	585	-1978	-2754	138	**-94**	-4213	-4246
28	7	2012-03-30 7:14:11	145904120	441	-1925	-2735	**54**	-150	-4364	-4404
29	7	2012-03-30 7:14:35	145904032	374	-1836	-2663	**29**	-155	-4429	-4475
30	7	2012-03-30 7:15:04	145903936	298	-1722	-2558	**1**	-162	-4494	-4547
Probability				0	0,166666667	0	0,25	0,583333333	0	0
Average ABS [Hz]				924,75	1003,583333	1501,166667	245,75	194,33333	3093,75	3140,333333
Average [Hz]				924,75	-954,5833333	-1451	245,75	88	-2867,083333	-2879,333333
FRQ				145906925	145905045,4	145904549	145906245,8	145906088	145903132,9	145903120,7

The bold and underlined font in the above table designates objects which have the smallest frequency shift and is above radio horizon of ground station. The bold font designates objects which have smallest frequency shift but are below radio horizon of ground station. Object G (2012-006G) showed the biggest convergence to the recorded signals (58% convergent results). The second possible candidate is object F (25% convergent results). The rest of objects have small probability to be PW-sat satellite. It was calculated additional mean shift in frequency for objects G and F which are appropriately 88 Hz and 245 Hz what designates object G as PW-Sat. However, it should be taken into account that these differences are not big and may be not conclusive.

During laboratory tests of PW-Sat satellite at Space Research Centre by students of Warsaw University of Technology the precise downlink and uplink frequencies were never precisely estimated. There was used Icom IC-910 satellite transceiver which transmitter was set to 435.020000 MHz FM and receiver was set to 145.904600 MHz USB in order to establish communication link with satellite. Taking into account the 88 Hz correction for object G it can be assumed that that satellite is transmitting on frequency 145.906088 MHz. However, during laboratory tests it was observed that according to temperature the frequencies of satellite can change even by 1 kHz. Thus it can be assumed that good approximation for communication is downlink of **145.906000 MHz** and using orbit model for object **2012-006G**. Additionally it is consistent with experiences from tests in Space Research Center when one would take into account a shift of -1.5 kHz of receiver resulting from USB modulation and also possibility of automatic tuning of reception software in the range of ±1 kHz.

After 3 months of mission satellites launched by means of VEGA1 rocket were more separated from each other [Figure 7]. In such situation estimation of satellite position using directional antennas allowed to confirm previous calculations that object 2012-006G is PW-Sat satellite. Other object were also partially recognized [Table 4].
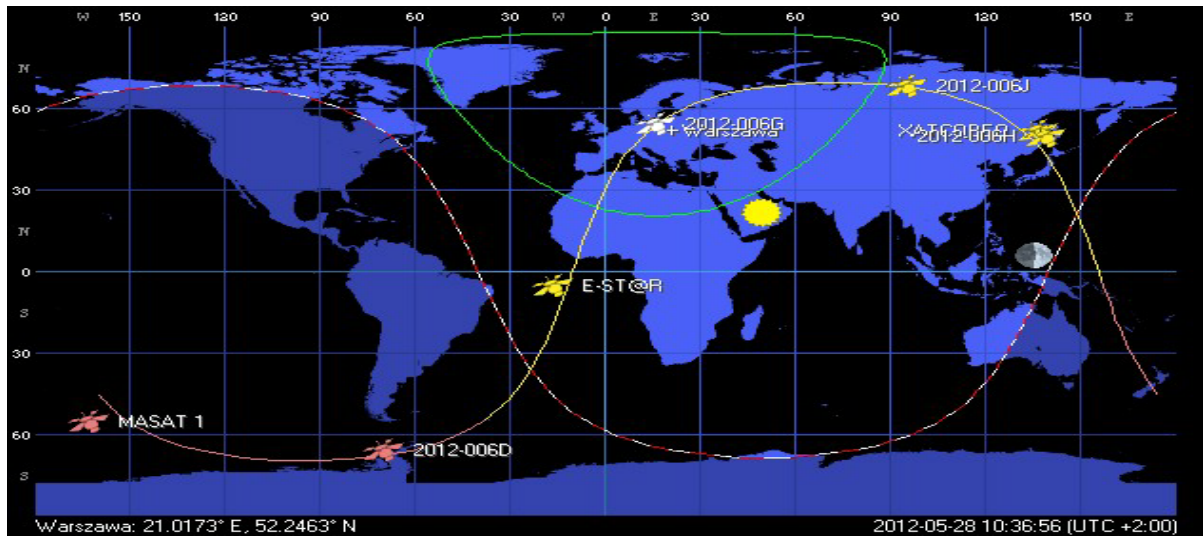
Figure 7. On-orbit distribution of objects detected by NORAD on 2012-03-30 (after 3 months from launch).

Table 4. Objects names status at 2012-05-28.

Object	Name
2012-006C	E-ST@R
2012-006D	Robusta (probably, inactive satellite)
2012-006E	MASAT 1
2012-006F	XATCOBEO
2012-006G	PW-Sat
2012-006H	None (not yet determined)
2012-006J	UNICubeSat GG or GOLIAT (not yet determined)

4. SUMMARY

This article presented the structure of PW-Sat's communication system. In the further part the problem with determination of satellite position in orbit was described. Next, a method for measuring frequency of PW-Sat satellite and a mechanism based on the Doppler effect allowing to determine the exact position of satellites in orbit were explained and the results obtained with this method were presented. Finally the measurements results confirming that above calculations were correct. The results of experiment described above will be used by ground station operation team to increase the probability of positive communication with PW-Sat.

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