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LIFETIME PERFORMANCES OF MODERNIZED GLONASS SATELLITES: A REVIEW

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ABSTRACT. GLONASS, successfully operating during 1990s became unusable by early 2000s. Following a revitalization and modernization plan since 2004, GLONASS constellation has been completed again by the end of 2011 and the use of GLONASS is gaining popularity. Because of the previous experience, some scepticism exists among the stakeholders in using GLONASS for reliable solution and application development. This paper critically reviews the operational lifespan of GLONASS satellites launched between 2004 and 2016, as this is an important contributor towards reliability and sustained operation of the system. For popularization and extracting full benefits of GLONASS as stand-alone system or as an active component of multi-GNSS, major issues of assuring the minimum sufficient GLONASS constellation (of 24…23 satellites), efficient design implementation and the modernized ground control segment development and operation need to be properly taken care of by the system operators.

Keywords: GNSS, Multi-GNSS, GPS, GLONASS Modernisation

1. INTRODUCTION

First GLONASS satellite was launched in 1982; an operational constellation was available from early January 1996, (Website of University of New Brunswick 2004-2016) providing the users an active and useful alternative to GPS, operating with Selective Availability during the period (Banerjee et al. 2002). The situation was short-lived, and the constellation gradually degraded (Holmes et al. 1998); it was observed, from 14 useable GLONASS satellites during May 1998, the number of satellites reduced to 06 in April 2001 (Rooney et al. 1999, and Banerjee et al. 2002) in the constellation. Naturally, reliable 3-dimensional position solutions were not possible and interest about using GLONASS diminished among the users.

Efforts for revival of GLONASS started from 2001 and by the end of 2011, GLONASS again became operational in its revitalized configuration (Langley 2011a, Voice of Russia 2011b). Variation of visible GLONASS satellites in the constellation from 1997 to early 2016 is shown in Figure 1. It is observed that since late 2011, enough number of satellites is present for using GLONASS. Consequently, users became aware of and interested to use GLONASS as a stand-alone alternative to GPS or as an active component of Multi-GNSS (Shengyue et al. 2010, O'Driscoll et al. 2011, Ta et al. 2013, and Sarkar and Bose 2016).

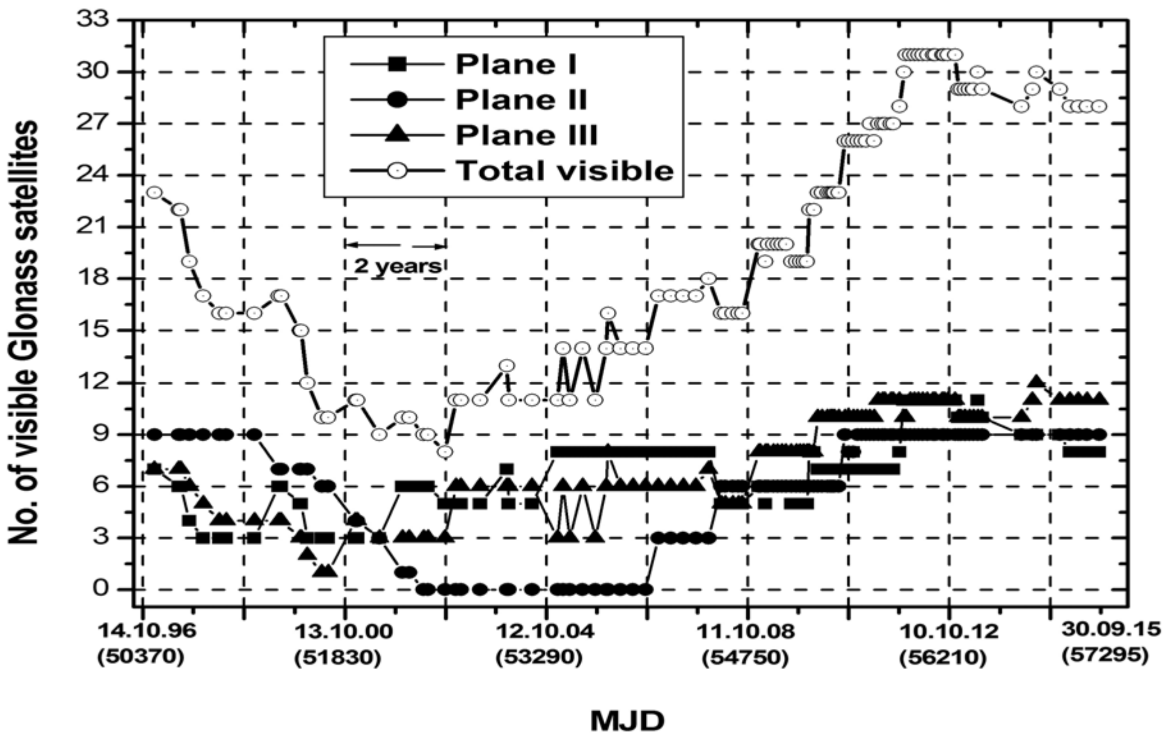

Fig. 1. Variation of visible GLONASS satellites numbers with time

GLONASS as an active alternative to GPS provides the users various advantages; one of these is availability of GNSS satellite signals in various degraded visibility conditions (e.g., urban canyon, deep foliage, open cut mines). In those limited visibility conditions, GPS and GLONASS can complement each other for seamless successful operation. A GNSS receiver is operated from different locations of India during 2012 in GPS+GLONASS mode with intentional high elevation cut-off angles of satellites to create an artificial degraded visibility situation. The results are shown in Table 1, wherein it is seen that, for 45^0 elevation mask, minimum requirement for 3d solution is attained only using GPS and GLONASS together. GLONASS operated in tandem with GPS also provides better solution accuracy over the standalone modes of operations (Sarkar and Bose 2016a).

Table 1. GNSS satellite usability with high elevation cut-off angles from different locations of India

Elevation Mask angle (degree)	Location	GPS sats in use (total GPS sats above 5^0 elevation angle)	GLONASS sats in use (total GLONASS sats above 5^0 elevation angle)
30	Chennai	5 (12)	4 (9)
	Balasore	5 (13)	4 (6)
	Pilani	5 (10)	4 (9)
	Burdwan	5 (9)	5(9)
45	Chennai	3 (13)	2 (10)
	Balasore	2 (12)	4 (9)
	Dehradun	3 (12)	3 (9)
	Burdwan	3 (9)	1 (8)

Another study is made to compare the performances of GLONASS and GLONASS-M class satellites in hybrid operation with GPS. With same number of GPS satellites (07), GLONASS satellites were introduced sequentially for position solution for few minutes keeping the satellite geometry similar. 3-dimensional solution errors of instantaneous solutions were calculated following Banerjee et al., 2002. Data collected in 2001 from Kolkata, India and collected in 2015 from Burdwan, India (the places separated by a distance of 100 km) are used and the results are presented in Table 2.

Table 2. Variations in 3d Errors using GLONASS and GLONASS-M along with GPS.

No of GPS used	No of GLONASS used	Avg 3d Error (m)		Standard Deviation of 3d Errors (m)	
		Year		Year	
		2001	2015	2001	2015
07	01	19.03	3.78	2.67	0.15
	02	14.38	5.00	0.42	0.53
	03	14.34	5.42	1.20	0.48
	05	13.62	5.47	0.30	0.24

From Table 2, it may be seen the new GLONASS-M class satellites, operating during 2015 are contributing in enhancing the accuracy of solution over those of 2001 in multi-GNSS hybrid operation. From the potential of GLONASS as an active component of multi-GNSS and enhanced performance capabilities, GLONASS is expected to generate enhanced interest among the GNSS user community.

However, because of the previous experience with declining GLONASS, some scepticism exists among the stakeholders in using GLONASS with high degree of confidence and reliability. A major factor governing the usability of a satellite constellation for reliable use is the satellites' operating life time. The incidence of sudden system failure during April 2014 (GPS World, 2014) was another concern of the GLONASS users. This paper presents a critical review of the life spans of the satellites of the revitalized GLONASS constellation. The paper starts with a brief discussion on GLONASS modernization plan, followed by the implementation history, the importance and improved performance of GLONASS; finally discussion on the newly launched GLONASS satellites' operational life spans is presented. These discussions may be useful in enhancing the reliability and confidence of the GLONASS user community to exploit the benefits of this fully operational system.

2. GLONASS MODERNISATION PLAN AND IMPLEMENTATION

In early 2000s, Russian President took special interest in GLONASS revival and in August 2001, the Federal Targeted Program "Global Navigation System 2002–2011" (Government Decision n.587) was launched. A budget of $420 million was allocated towards restoring the full constellation by 2009 (Atkins 2007a, RIA Novosti 2007a, 2007b). The three-phase program included sequential introduction of new and advanced GLONASS-M and GLONASS K (K1, and then K2) classes of satellites as successor of GLONASS satellites. Following this, between December 2004 and April 2017, 42 satellites have been placed into the constellation populating each of the three orbits, the last one being on 29 May 2016. A review of the evolution of GLONASS is presented by Langley (Langley 2017).

The revitalization process of GLONASS since 2004 has been studied in this paper using information from the official website “Information Analytical Centre (IAC) of Russian Federal Space Agency and other available sources (Federal Space Agency Information Analytical Centre 2004-2016, Website of The affiliated branch Precision Navigation and Ballistic Support of OJSC, University of New Brunswick (2004-2016), Banerjee et al. 2002, Bose et al. 2008, 2010, 2013, Shengyue et al. 2010, Russian system of differential correction and monitoring (SDCM) (2010-2016), O’Driscoll et al. 2011, Kahvecioglu 2011, Ta et al. 2013, and Sarkar and Bose 2016, O Montenbruck et al. 2015, Gunning et al. 2017, R B Langley 2017).

GLONASS modernization process was initiated in 2001, the implementation of the plan initiated in 2004. So, to begin the discussion, launching history of GLONASS satellites since 2004 is shown in Table 3 as the basis for analysis, wherein the satellites currently in operation are marked with bold font faces. In the right-most column, these satellites are assigned a number as per their launch sequence beginning from 2004 and these numbers would be used in a subsequent sections.

Lifespans of the GLONASS satellites launched since 2004 are now analysed to review the capability of these new spacecrafts towards establishing a stable and reliable constellation.

Table 3: Launching of GLONASS satellites and status as on 20 April, 2017

Launch Date	Nos	Plane no (slot), GLONASS SV# and **current status**			Assigned no to satellite*
25/ 12/ 2004	03	I (7), 712, NO	I (1), 796, NO	I (8), 797, NO	1, 2, 3
25/ 12/ 2005	03	III (24), 713, NO	III (23), 714, SP	III (19), 798, NO	4, 5, 6
25/ 12/ 2006	03	II (14), **715**, **OP**	II (15), **716**, **OP**	II(10), **717**, **OP**	7, 8, 9
26/ 10/ 2007	03	III (17), 718, NO	III (20), **719**, **OP**	III (19), **720**, **OP**	10, 11, 12
25/ 12/ 2007	03	II (13), **721**, **OP**	II (9), 722, NO	II (11), **723**, **OP**	13, 14, 15
25/ 09/ 2008	03	III (18), 724, NO	III (21), 725, NO	III (22), 726, NO	16, 17, 18
25/ 12/ 2008	03	I (3), 727, NO	I (2), 728, NO	I (8), 729, NO	19, 20, 21
14/ 12/ 2009	03	I(1), **730**, **OP**	I (4), **733**, **OP**	I (5), **734**, **OP**	22, 23, 24
02/ 03/ 2010	03	III (22), **731**, **OP**	III (23), **732**, **OP**	III (24), **735**, **OP**	25, 26, 27
02/ 09/ 2010	03	II (9), **736**, **OP**	II (12), 737, CHK	II(16), 738, NO	28, 29, 30
26/ 02/ 2011	01	III (4), 701/ 701K/ 801, Flight Testing			31
02/ 10/ 2011	01	I (4), **742**, **OP**			32
04/ 11/ 2011	03	I (2), **743**, **OP**	I (3), **744**, **OP**	I (7), **745**, **OP**	33, 34, 35
28/ 11/ 2011	01	III (17), 746, NO			36
26/ 04/ 2013	01	I (2), **747**, **OP**			37
24/ 03/ 2014	01	III (18), **754**, **OP**			38
14/ 06/ 2014	01	III (21), **755**, **OP**			39
01/ 12/ 2014	01	II (9), **702/ 702K**, **OP**			40
07/ 02/ 2016	01	III (17), **751**, **OP**			41
29/ 05/ 2016	01	II (11), **753**, **OP**			42
Legends: NO- Not in operation; **OP- In operation**; SP- Spare; CHK- Under Check by Satellite Prime contractor (SPC), Maint-Maintenance; *Number is assigned according to the launch sequence from 2004					

3. GLONASS SATELLITES' LIFETIME

As shown in Table 3, the 42 GLONASS satellites put into the orbits through 20 launches between 2004 and 2017. The planned completion of the constellation however, was delayed; the first decalred target for full constellation of 24 satellites was the year 2009 (Atkins 2007), but by the end of that year, out of the 22 satellites in constellation only 15 were operational. The second target of 2010 was marginally missed with 23 satellites in constellation (21 in operation). Revitalization process of GLONASS constellation was finally completed by 2011 and as on 01 December 2011, 31 satellites were avialable with 23 operational in the constellation (Langley 2011).

Observing the launch pattern presented in Table 3, it is seen that all the 11 launches between 2004 and 2010 and one in 2011 carried 03 satellites each, and all the satellites through a launch were placed in the same orbit. Since 2011, 08 launches with single satellite was witnessed. This may have been done according to the system revival plan- firstly towards rapid completion of the constellation to bring it into full operating condition and then to replenish the orbital slots as per operational needs. Now, based on detailed analysis of available information, the new GLONASS satellites' actual life spans are shown in a concise Table 4 vis-à-vis their design lifetimes; here the satellites are categorized according to their launch year and class. For construction of this table, widely scattered online resources and literature were collected, consulted and analyzed. Collected information was consolidated, cross-referenced and validated; final text presents concise information on the satellite life spans, those are otherwise available over widely scattered sources. In Table 4, dates of first outages after initiation of operation and reintroduction of the satellite to operation after the maintenance are also shown. The final outage/ end of operation date for a GLONASS satellite are marked using bold font face; satellites those are now operating without interruption since the initiation of operation are separately marked.

Table 4: GLONASS satellites' operational lifetime (as on 20 April 2017)

Launch year	GLONASS (Nos) Class	Design lifetime (Years)	Outage/ **Final outage** on	SV # and service reintroduction date	SV # operating without outage till 20/04/17	Achieved Lifetime and exceptions (Years)
2004 (25.12.04)	(03) GLONASS/ GLONASS-M	3- 4.5	**796 (04.05.08)** **797 (16.06.08)** 712 (05.04.08)	712 (01.09.08) as spare since 14.12.11, operation ends **22.11.12**	NONE	~3.5 #712 ~8)
2005 (25.12.05)	(03) GLONASS/ GLONASS-M	3-4.5	**798 (09.07.07)** **713 (31.03.09)** 714 (14.04.09)	714 (15.02.11 operation ends **24.02.16**)	NONE	~1.5 713~3.25 #714>11
2006 (25.12.06)	(03) GLONASS-M	7	715 (24.10.10) 716 (11.06.12)	715 (15.04.11), 716 (01.07.12)	717	> 10
2007 (26.10.07 25.12.07)	(06) GLONASS-M	7	722 (14.05.08) 723 (27.09.09) **718 (29.11.10)**	722 (01.09.08 operation ends **12.10.11**), 723 (25.10.09)	719, 720, 721	> 9 #722< 4, #718 ~3
2008 (25.09.08, 25.12.08)	(06) GLONASS-M	7	**726 (31.08.09)** **727 (08.09.10)** **729 (10.09.12)** **724 (12.02.14)** **725 (02.08.14)** **728-no record after 15.03.14**	None	None	~1- 5.5
2009 (14.12.09)	(03) GLONASS-M	7	733 (01.10.10)	733 (15.12.10)	730, 734	> 7
2010 (02.03.10, 02.09.10)	(06) GLONASS-M	7	**737 (15.02.16)** **738 (15.02.16)**	None	731,732, 735,736	> 6.5 #737, #738 ~ 5.5
2011 (26.02.11, 02.10.11, 04.11.11, 28.11.11)	(06) GLONASS-K, GLONASS-M	10-12 (K), 7 (M)	743 (04.05.12) **746 (13.04.15)**	743 (20.09.12)	701-Flight test 742, 745, 744	> 5.5 # 746 ~ 3.5 #701-Flight Test
2013 (26.04.13)	(01) GLONASS-M	7	**---**	---	747	>4
2014 (24.03.14, 14.06.14, 01.12.14)	(03) GLONASS-M, GLONASS-K	7 (M), 10-12 (K)	None	702 (GLONASS-K) in operation from 15.02.16	754, 755, 702	> 3
2016 (07.02.16)	(01) GLONASS-M	7	---	---	751	> 1
2016 (29.05.16)	(01) GLONASS-M	7	---	---	753	>11 months

Results presented in Tables 3 and 4 are again consolidated in Table 5 with information on the current operating SV #, orbital slot, and achieved lifetimes (in years); except SV #702 (GLONASS K1), all currently operating satellites are of GLONASS M class. It is also seen that, all the current operating satellites are launched in or after December 2006 and have started operation since early 2007. Orbit plane #2 and #3 of the GLONASS constellation currently contains 05 (#717, #723, #721, #715, #716), and 02 (#720, #719) satellites respectively those are operating beyond their design lifetimes. For assured system operation, proper attention of the system operators is required to this fact. Cumulative outage periods for the satellites launched from 2004 are separately tabulated in Table 6.

Table 5: GLONASS constellation status and operation life-time (as on 20 April 2017)

Plane	**Usable**/ (Available)	Orbital slot, and GLONSS SV # in slot and (life-time (years)) [Cumulative outage (months)]							
I	**8** (8)	1	2	3	4	5	6	7	8
		730 (7.35) [0]	**747** (3.98) [0]	**744** (5.47) [0]	**742** (5.55) [0]	**734** (7.35) [0]	**733** (7.35) [2]	**745** (5.47) [0]	**743** (5.47) [0]
II	**8** (9)	9	10	11	12	13	14	15	16
		702 (2.38) [0]	**717** (10.33) [0]	**753** (0.892) [0]	**723**/737 UC (9.33/6.63) [1/2]	**721** (9.33) [0]	**715** (10.33) [6]	**716** (10.33) [1]	**736** (6.63) [0]
III	**8** (10)	17	18	19	20	21	22	23	24
		751/714 (1.2/11.33) [0/24]	**754** (3.075) [0]	**720** (9.49) [0]	**719**/701 FT (9.49/6.15) [0/0]	**755** (2.85) [0]	**731** (7.14) [0]	**732** (7.15) [0]	**735** (7.15) [0]
Total	**24** (27)								

Note: SV 701 is still under flight test phase, UC-Under Check, FT-Flight Test

To understand the GLONASS satellite lifetimes and constellation maintenance since 2011, careful analysis of the information provided by the sources discussed above leads to the following comments and these are summarized in Table 7.

- Total number of scheduled maintenances over 2011-2016 is 114 and total number of unscheduled maintenances is 05, much lesser than the scheduled ones. Only 01 satellite has gone for long-term (~1 month) scheduled maintenance. Most of time, expected maintenance period are not declared beforehand.
- Despite of scheduled maintenance of all satellites in constellation over this time, 05 have stopped their work suddenly and gone for unscheduled maintenance and 06 SVs are declared directly to complete outage stage and are removed from the orbits.
- One may witness that the cumulative outage times for the currently operating satellites are significantly low.

Table 6: Cumulative outage period of GLONASS satellites

Launch Year	GLONASS SV#	Cumulative outage period (months)
2004	712	16
	796	0
	797	0
2005	713	0
	714	22
	798	0
2006	715	6
	716	1
	717	0
2007	718	0
	719	0
	720	0
	721	0
	722	4
	723	1
2008	724	0
	725	0
	726	0
	727	0
	728	0
	729	0
2009	730	0
	733	2
	734	0
2010	731	0
	732	0
	735	0
	736	0
	737	0
	738	0
2011	701/701K	0
	742	0
	743	4
	744	0
	745	0
	746	0
2013	747	0
2014	754	0
	755	0
	702/702K	0
2016	751	0
	753	0

Table 7: GLONASS satellite maintenances during 2011 to 2016

Scheduled Maintenances						Unscheduled Maintenance	
Exact maint. time not declared	Maint time ~ Few hours	Maint time ~1-12days	Maint. Time ~1 month	Direct outage	Maint time ~ 1- 25 days for making change in slot	~1 month	Maintenance time not declared
37	37	31	1	6	2	2	3

Through critical analysis of the GLONASS current operational status, satellite lifetime and outage patterns the follwing may be concluded.

- GLONASS class satellites launched in 2004 have achieved their lower limit of design lifespans of around 3.5 years and average uninterrupted lifespan is 3.4 years, whereas, the first GLONASS M class satellite launched at the same time was successfully exceeded its design lifetime of 7 years.
- The last GLONASS class satellite was #798, which had comparatively shorter lifetime of 1.5 years. GLONASS M classes were introduced with larger design lifetime among which #713 has failed to achieve its desing lifetime and actively worked only for 3.25 years.
- First GLONASS M class Satellites launched in 2004 and 2005 are put into service approximately after 01 year from their launch dates. SV #714 went through maintenace of 2 years; followed by re-introduction in operation and it finally stopped operation in February 2016 after more than 10 years of total service. Change of operational slots in the same orbital plane has also been observed.
- GLONASS M Class satellites launched in 2004, 2005 and 2006 started their operation within 7 months to 1 year from respective launch dates; whereas, the GLONASS M class satellites launched in or after 2007 began their opration approximately after 1 month of launching. Among these, 01 (#713) failed to achieve it's design life-time; 03 (#715, #716, #717) of them are the oldest satellites in current constellation offering more than 9 years of service exceeding their planned lifespan by nearly 2 years.
- In last quarter of 2007, 06 GLONASS M satellites were launched; out of the first three, #718 stopped operation completely within 3 years of launch and out of the next three, SV #722 and #723 went into maintenance within six months and two years respectively. Except for SV #718, the other two SVs (#722 and #723) came back to operation within a short period of time though SVs #722 stopped operation with less than 04 years' lifetime. Except SV #718 (~3 years) and SV #722 (< 4 years), the other 04 satellites launched in 2007 have achieved their design lifetime of 7 years.
- In second half of 2008, 06 GLONASS M satellites were put into the GLONASS orbits III and I through 02 launches. Interestingly, all of these have gone out of operation within approximately 1-6 years but SV #725 is still present in Slot 21, Plane III with "under check by Satellite Prime Contractor" status. Therefore, none of the M-class satellites launched in 2008 could achieve their design lifetime.

- December 2009 witnessed launch of 03 more GLONASS M satellites in orbit; two (SV #733, #734) are operating without interruption while SV #733 was in maintenance for a brief span of two months- thus have crossed their 7-year design lifspan.
- Through two launchs in first and third quarter of 2010, 06 GLONASS M satellites are put into the constellation. SVs #737 and #738 stopped operation after 5.5 years of active service and the other 04 are operating uninterruptedly. It is to note that few of the satellites launched after 2010, are put into "spare" state over some timespan; so by this time, GLONASS constellation is optimally populated for operation and advance measures are taken to replenish non-functional satellites quickly for assured service.
- Total 06 satellites were launched in 2011 through 04 launches with the first GLONASS K (SV #701/ 801, Class K1) satellite in the top of the list and the other 05 being GLONASS M spacecrafts. SV #701 is still in "Testing Phase" and SVs #742, #744, #745 are operating without break. SV #743, with a brief maintenance period of 04 months is in operation, and SV #746 stopped operation since April 2015. Out of the 05 GLONASS M satellites launched in this year, 04 are operational for more than 5.5 years.
- 03 GLONASS M satellites and 01 GLONASS K1 satellite are launched during 2013-2014; the M-class birds are operating without outages and #702 is the first GLONASS K class satellite to initiate operation in February 2016. February 2016 also witnessed the last GLONASS M launch; SV #751 started operation within 03 weeks of launching.

Based on the above discussion, lifespans of GLONASS M satellites vis-à-vis their design lifetime of 7-years are summarized in Table 8. It may be noted that, for the satellites launched from 2010 onwards, achievement of design life cannot be fully judged as we are reviewing the situation at around 6.5 years; but the information on the maintenance and failures shown in Table 4 helps to judge the operational capabilities of these satellites.

Table 8: Lifespan GLONASS M satellites

Launch Year	No of GLONASS M satellites		
	Launched	Achieved Design life/ (operating for, years)	Failed to achieve design life
2006	03	03	Nil
2007	06	04	02
2008	06	00	06
2009	03	03 (> 7 years)	Nil
2010	06	04 (> 6.5 years)	02
2011	05	04 (> 5.5 years)	01
2013	01	01 (> 4 years)	Nil
2014	02	02 (> 3 years)	Nil
2016	02	02 (>1year)	Nil
Total	**34**	**-**	**11**

Launch of the first GLONASS-K1 satellite (SV #701) with longer design lifespan was delayed from the original schedule; being put into orbit in February 2011, after more than 06 years, it is still in "Testing Phase". Second K1 Class satellite (#702) was expected within a year of the first launch; however, due to problems with the satellite and the launch vehicle, priority was given in GLONASS M launches to maintain the functionality of constellation. Losses of spacecraft during Proton launch failures in 2010 and 2013 delayed the launch of #702 by long time, finally it was launched in December 2014 and is put into operation just after 1 year.

Figure 2 shows the summarized results on the GLONASS satellite lifetimes, wherein the achieved lifespans are shown along with the design lifetime for each of the GLONASS satellite launched since 2004. For convenience, satellites are assigned a sequential number as per launch sequence since 2004 as described in Table 3. Older GLONASS class satellites barely achieved the lower limit of design lifetime. Early (2007, 2008) M Class satellites also had higher rate of failure in achieving design lifetime in comparison to those launched during 2009 onwards. Enhanced operational life, lower requirement of maintenance and lower outages of these new SVs point towards the improvement of the system from the satellite lifespan point of view.

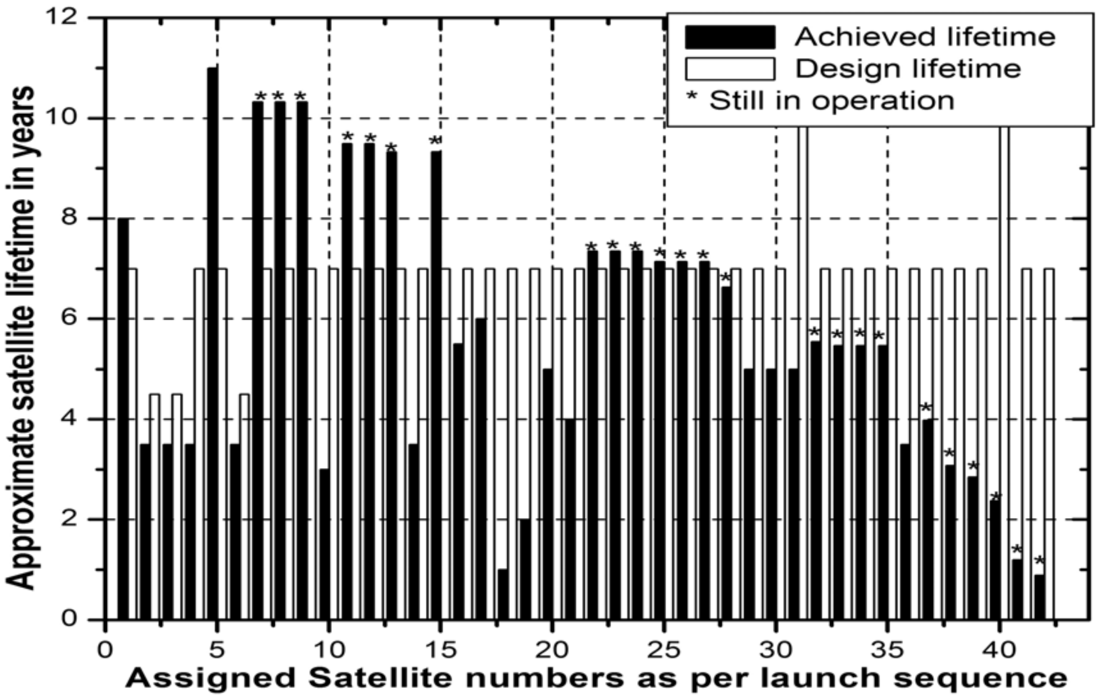

Fig. 2. Comparison of design and achieved lifetime of GLONASS satellites launched

Note: Satellites number are assigned according to their launch serial since 2004, Ref: Table 3)

4. CONCLUSIONS

GLONASS became fully usable since end-2011; currently it is a fully operating alternative to GPS, and has vast potential as an active component of hybrid Multi-GNSS operation. However, to exploit the advantage of the situation, confidence and reliability on GLONASS should be assured and enhanced for the associated stakeholders. Early GLONASS class satellites had very small lifetimes, which may be one of the reasons for GLONASS degradation in early 2000; but the new GLONASS M and K Classes of satellites have claimed higher design lifetime of 7-10 or more years for uninterrupted and reliable operation. This review shows that many of the early GLONASS M satellites failed to achieve the design lifetime, and the situation improved much in subsequent years that underpins the effort of the system operators in maintaining assured stability of GLONASS service.

For popularization and extracting the possible benefits of the fully operating GLONASS with high degree of confidence, quality assurance, efficient design implementation and system maintenance are the major issues those should be efficiently addressed by the system operators. Issues like GLONASS system failures during April, 2014 should also be reviewed properly and information on the remedial measures against such incidents must be available in public domain for users' confidence enhancement. In future, the stakeholders of GLONASS would look forward for new launchings and active operation of K1 and subsequently of K2 class of satellites. Users also would expect to use GLONASS to extract full advantages of the existing Multi-GNSS environment in cost-effective, real life applications with enhanced confidence and assured reliability.

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