Analysis of RSO's Close Approaches with the ISS During Two Years Flight

V. M. Agapov(1), Z. N. Khutorovsky(2)

(1) *KIAM RAS, Miusskaya Sq., 4, Moscow, Russia*
E-mail: avm@kiam1.rssi.ru
(2) *Vympel ISC, 8 Marta Str., Moscow, Russia*

ABSTRACT

On Nov 20, 1998 the first module of the ISS – Zarya, was successfully launched from Baykonur cosmodrome. On Dec 6 1998 another module – Unity, was docked to Zarya and since that almost two years, till Jul 2000, the ISS had been orbiting the Earth in such configuration, sometimes changing it with rare Shuttle visits. It is interesting to analyze the orbital "vicinity" of the ISS during this period of relatively stable flight with minimal amount of dynamical operations.
A posteriori analysis of whole orbital archive revealed some close approaches with the ISS. Technique of close approaches calculations and archive maintenance will be discussed in this presentation.

1. METHODS OF RISK ANALYSIS

There are two different techniques used for estimation of orbiting objects (RSOs) collision risk. These are statistical and deterministic.
The first one uses probability distributions of space objects in space depending of parameters of some kind, i.e. averaged data [1,2]. Real motion in time of the whole objects amount is approximating by random process of specific kind. The peculiarities of separate objects are not taking into account. Simplified assumptions are considered for prediction of probability of object distributions. As a result we have modeling errors. Sometimes using of the statistical approach gives results with the lack of accuracy, especially when we would like to calculate collision probability for specific objects.
Deterministic technique uses information on all known space objects (geometry, orbit at the given time, accuracy estimations of this orbit) as a base for calculations [3]. Using such approach we can obtain so called “close approaches archive”. It contains comprehensive information on all close approaches which took place between any two RSOs. So, we don’t loosing information and are able to obtaine more accurate results [4].
However, deterministic approach couldn’t be used in some tasks. For example, you can’t use it for calculations of close approaches with uncataloged objects and for propagation of the risk for the long future. Such tasks require both techiques to use with the deterministic one as a basis, if possible.

2. CLOSE APPROACHES

For common understanding, the term “close approach” hereafter will be used for approach of two objects at the distance less or equal to a given distance (usually 3-10 km), or approach with valuable probability of collision (usually, greater than 10^{-11}).
Calculation algorithm permitting to find all close approaches for any pair of objects at a given time frame well described in [3]. Time and spatial characteristics for each discovered close approach are calculated as well as probability of collision.
Here is computation formula for collision probability:

$$P_c = k \cdot exp(-0.5 \cdot (k_{rr} - k_{rv}^2\, k_{vv}^{-1}))$$
$$k = S \cdot v_r \cdot (4\pi^2 k_{vv} det\mathbf{K_1}\, det\mathbf{K_2}\, det(\mathbf{K_1}^{-1} + \mathbf{K_2}^{-1}))^{-0.5}$$
$$k_{rr} = \delta\mathbf{r}(\mathbf{K_1} + \mathbf{K_2})^{-1}\delta\mathbf{r}^T$$
$$k_{vv} = \delta\mathbf{v}(\mathbf{K_1} + \mathbf{K_2})^{-1}\delta\mathbf{v}^T$$
$$k_{rv} = \delta\mathbf{r}(\mathbf{K_1} + \mathbf{K_2})^{-1}\delta\mathbf{v}^T$$

where
$\delta\mathbf{r}$, $\delta\mathbf{v}$ – vectors of relative position and velocity for approaching objects
$\mathbf{K_1}$, $\mathbf{K_2}$ – correlation matrixes of errors in position for each of objects
v_r – absolute value of relative velocity
S – collision cross-section

These expressions had been written on following considerations:

1. Relative motion is going along straight line
2. Relative velocity determination errors are insignificant
3. Positional errors for at least one of objects are much bigger than geometry size of another one

3. METHODS OF RISK EVALUATION

As stated earlier, close approaches archive on a long time span is an informational basis for risk evaluation and description of an uncataloged objects population.

Proceedings of the 3rd European Conference on Space Debris, ESOC, Darmstadt, Germany, 19 - 21 March 2001
(ESA SP-473, August 2001)

Using the archive along with traditional methods of mathematical statistics we can directly estimate distribution of any parameter which was calculated and stored. And this distribution will reflect not modeled but real data.

If this simple technique will be applied to some specific objects we'll obtain results depending of which time frame analysis is making. However, it's interesting to obtain average parameters for hypothetical object having given sizes and orbital parameters. Such data could be also obtained from the close approaches archive if there is enough similar objects on orbits with similar parameters.

For averaging of the collision probability for all object on close orbits it should be re-calculate all stored probabilities in the archive to some reference size d_0:

$$P_{c,new} = P_c \cdot \frac{(d_0 + \tilde{d})^2}{(d + \tilde{d})^2}$$

where

P_c and $P_{c,new}$ – initial and re-calculated probabilities of collision

d – size of object for which probability of collision is calculating

$\tilde{d}$ - size of approaching object.

After such re-calculation is made we can average characteristics of different objects.

So, using the archive of close approaches it is possible to obtain averaged characteristics of collision risk for whole time span the archive is covering. In turn it permits to analyze changes of these characteristics in time.

4. CLOSE APPROACHES CALCULATIONS SOFTWARE

Based on described algorithms there were developed by authors task for programming and the special software had been written by the Russian *KIASystems* company. The software created under the Linux operational system and is integrated with the Catalogue tools developing by the same company. With this software there was calculated archive of close approaches for whole catalogue, including LEO, GEO and other cataloged objects for which we have orbital data (TLEs, state vectors). For initial testing there was choosen time span of 1996-2000. There are total about 13.5 millions of orbits for more than 10000 objects in this time span.

Intensive testing of this software had been done by authors jointly with programmers this February and now it is fully operational. Calculation time for searching of all close approaches between any pair of cataloged objects on one day time span is varying from 12 to 13.5 minutes depending of number of objects for which orbital information available for this day. These digits were obtained for PC with 800 MHz Pentium III-type processor and 128 Mb of memory. So, it's clear that the whole calculation time for one year time span requires from 3 to 3.4 days of processor work. Since the software is permitting to run child process under control of the parent process on the server it is possible to use any number of PCs working simultaneouthly. So, using, for example, three 800 MHz Pentium III PCs we can calculate close approaches archive for time span 3 years just in 3-3.5 days.

This archive served as a basis for all follow-up analysis.

General results of analysis are presented on figures at the end of this article.

Criteria of close approach was following:

- probability of collision is greater than 10^{-11} or the relative distance is less or equal to 5 km
- relative velocity is greater or equal to 15 m/sec

The latest criteria was used to avoid calculations of "false" close approaches between cooperating objects keeping some relative orbital configurations determined by operational needs.

Some analysis was made for time span Jan 1, 1998 Jul 1, 2000.

It is interesting to see how changes overall daily number of close approaches versus time (Fig. 1). You can see that mean number was decreasing constantly during 1998 –1999 and till March 2000. Probably, this could be explained by decay of the most number of fragments created as result of the HAPS stage fragmentation (1994-029B) in June 1996. Significant increasing of close approaches number since last March is due to explosion of the CZ-3 upper stage (on Mar 27) in highly populated spatial area.

Daily probability of collision versus time is shown at Fig. 2. You see that during last two years it's value was relatively stable for whole catalogue. As for specific regions it should be additional analysis made.

Daily number of most dangerous close approaches (less than 1 km in total and less than 0.5 km in particular) versus time is shown on Fig. 4.

5. CLOSE APPROACHES IN VICINITY OF THE ISS

More than 6 millions of close approaches met criteria described above were found on time span 1996-2000. Of this number there were selected those have occurred with the International Space Station since it's launch on Nov 20, 1998 till the launch of Zvezda module last July. All such approaches are summarized in the table 1. For each event the following parameters are given:

- number of the primary object (ISS, #25544) and the approaching object in the Catalogue of the U.S. Space Command

- date and time the close approach took place
- nodal period for each object at the time of the event, min
- inclination of orbit for each object at the time of the event, °
- relative distance at the time of the event, km
- relative velocity at the time of the event, km/s
- probability of collision
- “age” of epoch for each satellite’s orbit with respect to the time of the close approach

Probability calculations was based on average object sizes published monthly in the Goddard Space Flight Center’s Satellite Situation Reports.
It can be seen that close approaches have been occurring mostly with objects in orbits close to the ISS’ one by period. Almost all these objects were in natural decay regime. One of the (#16680) have produced 9 close approaches during two days due two close geometry of orbits in shape and size (but not spatial position).
To give you general imagination how many close approaches have occurring daily on heights between 300 and 420 km (where ISS-Soyuz-Shuttle-Progress operations are going) overall number of such approaches had been calculated from the archive and presented at Fig. 3. It is seen that close approaches at these heights are rare events. This fact is explaining by significant perturbations caused by Earth’s atmosphere in this region.
Some concerns exists due to close approaches with objects on highly elliptical orbits. Usually the orbit’s accuracy for small objects on such orbits is significantly lower than for LEO ones. This particular question is under investigation at present.

6. REFERENCES

1. Johnson N.L., McKnight D.S., *Artificial Space Debris*, Krieger Publishing Company, Malabar, Florida, 1991.

2. A.I.Nazarenko, Prediction and Analysis of Orbital Debris Environment Evolution, *Proc. of the First European Conference on Space Debris*, Darmstadt, Germany, April 1993, pp.293-298.

3. Z.N.Khutorovsky, V.F.Boikov, S.Yu.Kamensky, Direct Method for the Analysis of Collision Probabilities of Artifisial Space Objects in LEO: Techniques, Results and Application, *Proc. of the First European Conference on Space Debris*, Darmstadt, Germany, April 1993, pp.491-508.

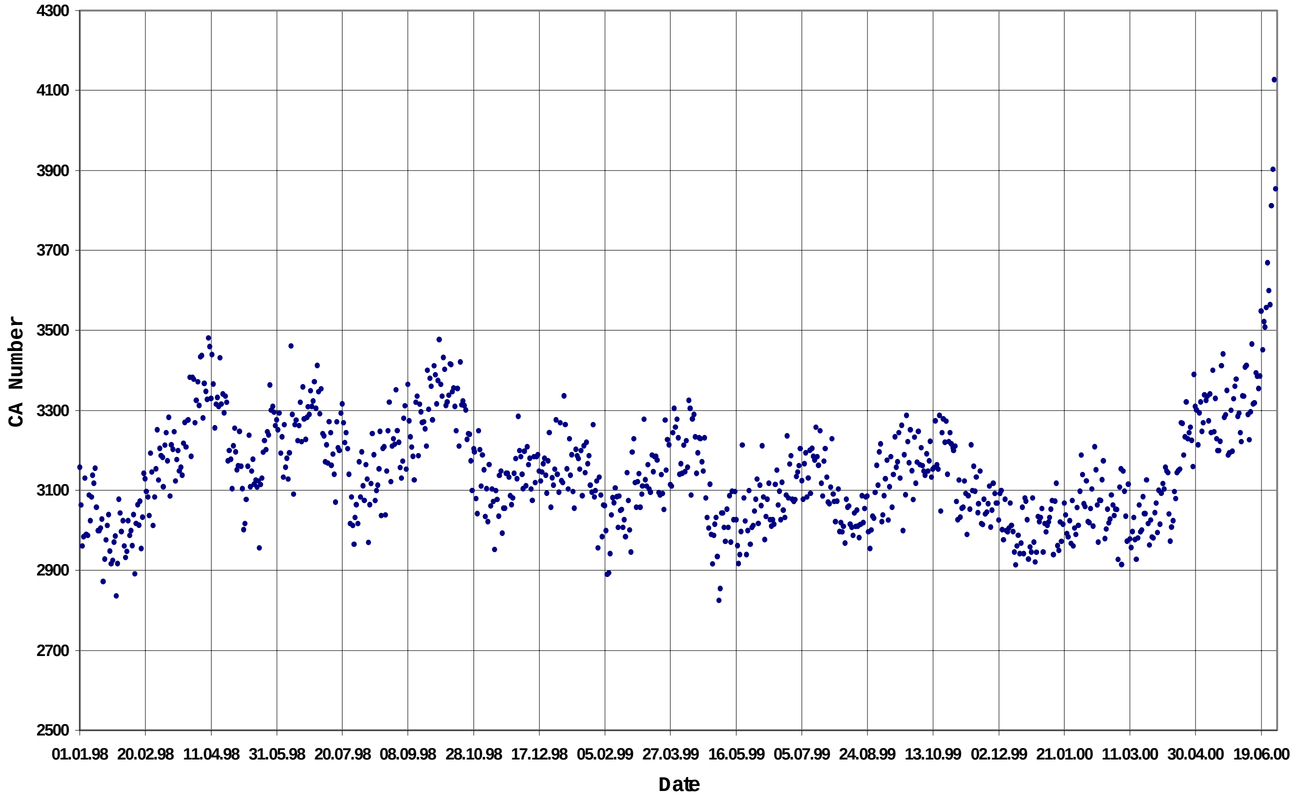
4. З.Н. Хуторовский, С.Ю. Каменский, В.Ф. Бойков, В.Л. Смелов, Риск столкновения космических объектов на низких высотах, Столкновения в околоземном пространстве (космический мусор), сборник научных трудов, Институт Астрономии РАН, Москва, Космоинформ, 1995, стр. 19-90 (in Russian)

Table 1. List of close approaches of the ISS with other RSOs during Nov 1998 – Jun 2000.

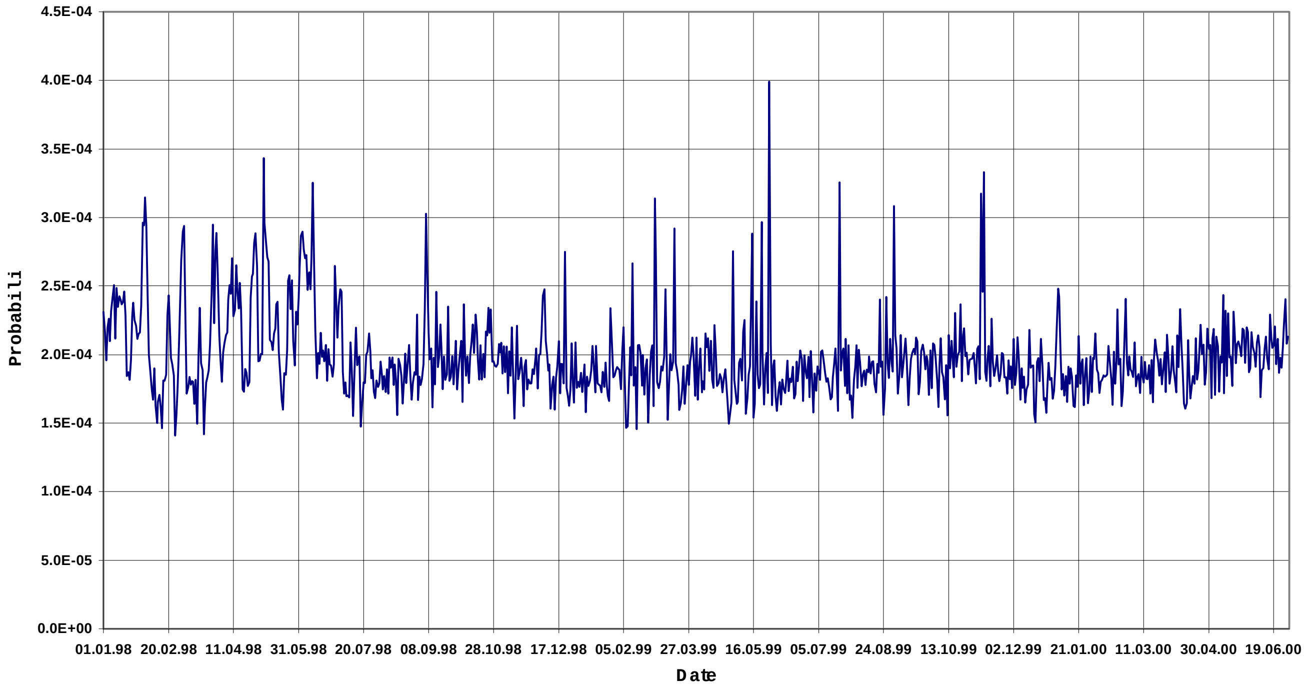
		Date/time of CA, UTC	T_1, min	T_2, min	I_1,°	I_2,°	dR, km	dV, km/s	P	$DEpoch_1$, days	$DEpoch_2$, days
25544	4221	30.11.1998 23:39:44.456	92.4745	109.8181	51.612	102.722	3.275	15.365	1.07591e-06	0.0975	-0.8391
25544	12139	11.12.1998 20:19:54.197	92.5147	104.2531	51.608	82.970	3.806	14.230	5.55877e-07	0.0046	-0.3300
25544	4053	16.12.1998 21:59:29.961	92.6132	118.4140	51.596	30.334	5.074	10.117	2.49063e-08	0.0026	-0.3802
25544	1844	26.12.1998 21:58:07.031	92.4839	92.7150	51.580	64.970	6.906	3.314	1.28710e-10	-0.1079	1.6339
25544	20047	06.01.1999 20:37:38.672	92.5823	92.3692	51.601	97.643	6.025	14.631	1.54727e-09	0.3150	0.1010
25544	8940	11.01.1999 21:04:44.500	92.4080	92.4423	51.573	98.324	5.572	12.380	5.84953e-09	-0.0166	2.6272
25544	8940	18.01.1999 23:30:02.141	92.4955	92.4546	51.589	98.320	6.283	14.371	7.12114e-10	-0.0552	0.9892
25544	17551	24.03.1999 12:14:30.604	92.2638	92.0739	51.575	98.448	5.014	13.274	2.57196e-08	0.0136	-0.2971
87618	25544	09.04.1999 21:02:55.687	108.1587	92.2535	60.729	51.579	0.766	9.404	1.18231e-05	-16.4809	-0.1398
25544	12388	03.05.1999 17:54:47.186	92.2220	105.4453	51.584	82.975	4.999	6.514	3.27505e-08	-0.3093	-0.2856
25544	25139	16.05.1999 09:31:04.486	92.3073	91.4377	51.603	28.544	6.543	4.145	3.21748e-10	0.0376	-2.3039
25544	20919	21.05.1999 04:05:11.364	92.3614	94.5244	51.613	24.751	6.235	9.506	1.25052e-09	0.0006	-1.7351
25716	25544	30.05.1999 22:37:06.056	92.3509	92.1318	73.499	51.578	1.925	11.008	5.52043e-06	-0.0555	0.0201
25544	1844	13.06.1999 13:31:07.966	92.2700	92.0248	51.572	64.957	7.414	7.007	2.08615e-11	-0.1432	-0.1494
25544	22902	17.06.1999 15:25:32.596	92.3735	92.1220	51.592	98.334	3.127	14.463	1.19075e-06	-0.5045	-0.1662
87345	25544	27.06.1999 03:31:55.138	92.4796	92.3235	78.886	51.587	1.827	5.155	5.94298e-06	-3.1569	-0.0096
25544	22935	06.07.1999 18:59:57.560	92.2849	92.5805	51.587	97.583	6.965	8.285	7.32139e-11	0.0220	-0.9408
25544	16084	29.07.1999 04:00:41.284	92.4053	92.2954	51.615	97.872	5.199	14.799	1.70654e-08	0.0013	-0.0970
25544	24373	19.08.1999 15:03:59.263	92.1240	92.5113	51.575	82.119	5.825	11.332	2.90588e-09	-0.1415	2.1613
25544	15053	28.08.1999 18:48:48.774	92.1008	327.8516	51.575	51.941	2.366	5.897	3.78299e-06	0.3652	-0.0151
25544	16084	22.09.1999 21:26:42.989	92.1731	92.0061	51.600	97.881	1.356	14.631	9.27379e-06	-0.0576	-0.1006
25544	15996	09.10.1999 22:31:35.583	92.1255	624.2088	51.602	25.896	2.971	7.646	1.90815e-06	0.5372	0.0186
25544	24831	28.10.1999 06:15:51.050	92.1534	99.4722	51.611	83.424	6.505	14.369	3.49249e-10	0.1612	-0.1391
25544	20919	21.11.1999 09:15:20.091	92.0226	93.1481	51.606	24.740	6.432	9.287	6.71326e-10	0.1616	-0.1329
25544	14484	26.11.1999 07:54:35.008	91.9989	103.1566	51.610	82.905	5.913	14.435	3.24416e-09	-0.1276	0.2507
25887	25544	01.12.1999 13:16:10.435	101.3803	91.9429	52.307	51.608	7.163	12.003	5.98043e-11	-0.3897	-0.2514
25544	16480	08.12.1999 14:22:39.398	92.2281	92.3375	51.598	97.766	7.503	14.625	1.06759e-11	-0.0419	-0.0911
25544	16480	08.12.1999 15:54:54.744	92.2254	92.3351	51.597	97.766	4.320	14.617	1.30019e-07	-0.1060	-0.1552

		Date/time of CA, UTC	T_1, min	T_2, min	I_1,°	I_2,°	dR, km	dV, km/s	P	$DEpoch_1$, days	$DEpoch_2$, days
25544	16480	08.12.1999 17:27:10.082	92.2232	92.3329	51.597	97.766	3.049	14.609	1.35188e-06	-0.1701	-0.2193
25544	16480	08.12.1999 18:59:25.409	92.2207	92.3306	51.597	97.766	4.607	14.601	6.85577e-08	-0.2341	-0.2833
25544	16480	08.12.1999 20:31:40.737	92.2182	92.3282	51.596	97.766	6.882	14.593	9.96512e-11	-0.2982	0.2939
25544	16480	09.12.1999 18:03:14.196	92.1832	92.2942	51.591	97.767	7.226	14.466	2.95395e-11	0.1174	0.4231
25544	16480	09.12.1999 19:35:29.374	92.1808	92.2915	51.591	97.767	4.706	14.456	5.44246e-08	0.0534	0.3590
25544	16480	09.12.1999 21:07:44.543	92.1782	92.2888	51.591	97.767	2.738	14.446	2.12076e-06	-0.0107	0.2950
25544	16480	09.12.1999 22:39:59.702	92.1757	92.2863	51.590	97.767	4.012	14.436	2.47087e-07	-0.0747	0.2309
25544	22822	20.12.1999 03:26:14.786	92.1798	92.2007	51.597	30.879	5.497	7.572	7.28434e-09	-0.2813	-0.0522
25544	14693	20.01.2000 09:14:23.904	92.1567	91.6789	51.610	28.153	5.680	3.126	5.10238e-09	-0.0956	0.1595
25544	20919	27.01.2000 03:41:15.536	92.1315	92.1867	51.609	24.740	5.399	3.575	1.42557e-08	0.0466	0.0959
25544	23281	21.02.2000 05:04:08.953	91.8286	101.1747	51.577	82.966	2.338	12.661	3.83109e-06	0.0154	0.0459
25544	16547	01.04.2000 17:31:36.471	91.6756	103.7695	51.595	60.684	5.835	12.317	2.73080e-09	-0.0655	-0.0051
25544	22670	11.04.2000 02:39:53.804	91.6543	462.9070	51.605	7.346	4.773	7.337	8.09031e-08	0.0178	0.3130
25544	11268	19.04.2000 03:34:44.246	91.4600	91.5150	51.584	81.183	4.916	13.380	5.61231e-08	0.0402	-0.3755
25544	23579	27.04.2000 01:31:15.593	91.3962	91.1421	51.587	51.649	7.706	10.371	2.41399e-11	0.1332	1.0041
25544	25234	04.05.2000 21:48:27.242	91.3146	91.5284	51.582	97.663	6.026	7.621	1.80284e-09	0.0040	-0.5153
25813	25544	09.05.2000 13:57:04.376	136.1204	91.3049	46.165	51.586	2.072	1.537	4.88177e-06	0.1029	-0.1059
25544	16609	25.05.2000 16:46:00.264	91.7937	92.0105	51.581	51.653	4.487	10.476	4.99899e-07	-0.0243	0.1840
25544	10362	28.05.2000 00:37:34.988	92.0068	91.7744	51.569	81.200	5.292	12.282	1.93807e-08	0.0872	-0.0399
25544	20406	30.05.2000 03:38:22.345	92.1314	284.7479	51.591	26.414	5.731	8.451	4.87178e-09	-0.1991	-0.0207
25544	24377	04.06.2000 09:19:47.606	92.1478	91.8060	51.595	81.993	2.377	4.274	3.35832e-06	0.0975	0.1880
25544	25031	06.06.2000 03:19:16.164	92.1584	92.7566	51.598	35.208	4.535	10.230	1.29843e-07	0.0543	-0.1968

Daily Number of Close Approaches vs. Time Calculated for Whole Catalogue



Daily Probability of Close Approaches vs. Time Calculated for Whole Catalogue



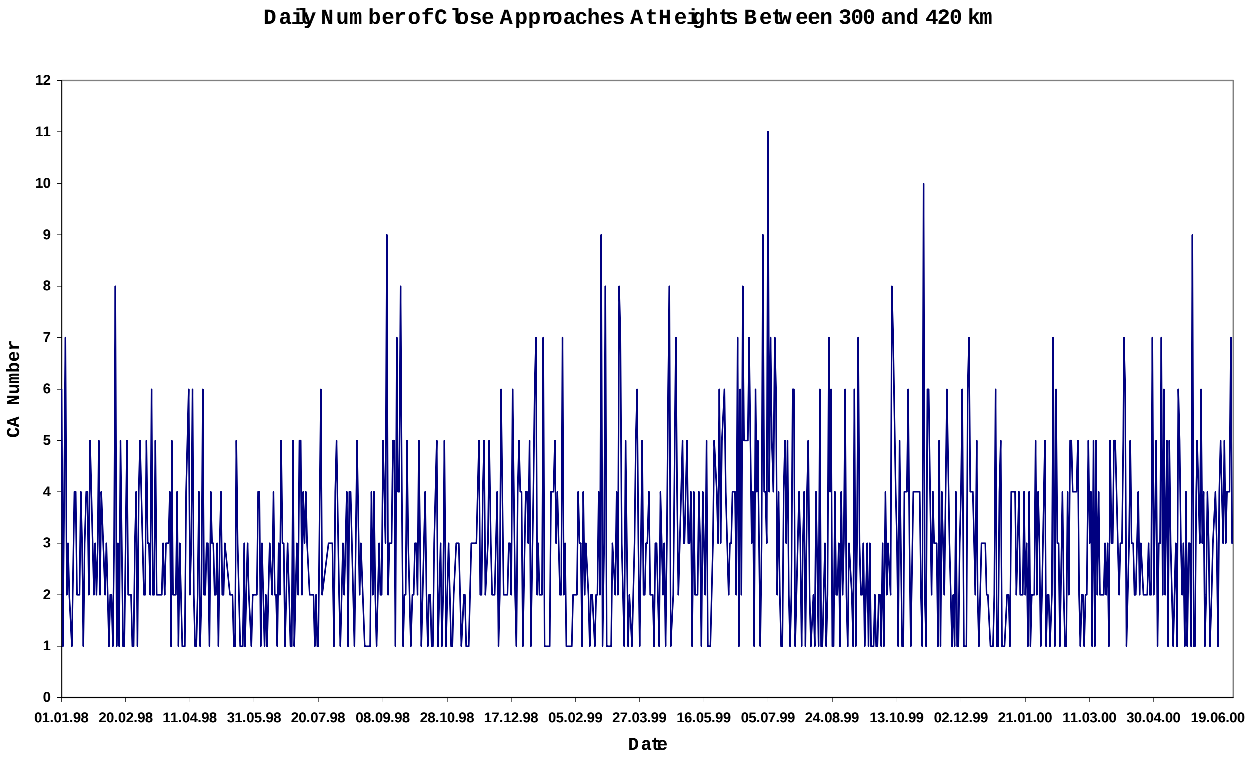


Fig. 3 Daily number of close approaches at heights between 300 and 420 km

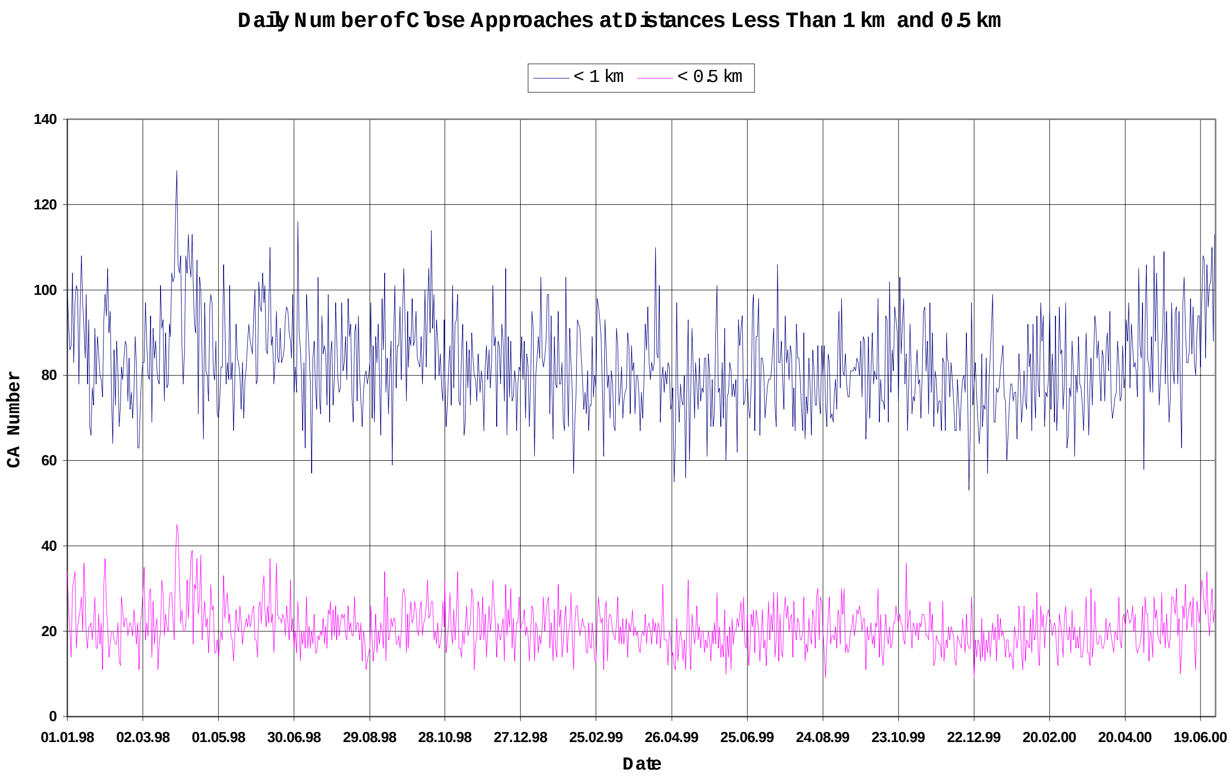


Fig. 4 Daily number of close approaches at distances less than 1 km and 0.5 km