# A DECADE OF GROWTH

**Phillip D. Anz-Meador**(1)**, Nicholas L. Johnson**(2)

*(1)Viking Science & Technology, Inc., 16821 Buccaneer Lane, Ste. 216, Houston, Texas, 77058, USA, panz-meador@vsti.com*
*(2)NASA Johnson Space Center, SN3, Houston, Texas, 77058, USA, nicholas.l.johnson@jsc.nasa.gov*

## ABSTRACT

This paper examines the Space Surveillance Network catalog's growth in low Earth orbit (LEO) and the geosynchronous Earth orbit (GEO) over the decade 1990-2000. During this time, innovative space utilization concepts, *e.g.* the Iridium and Globalstar commercial communication satellite constellations, have increased the public's consciousness of space. At the same time, however, these constellations have increased spatial density at their operational altitudes. Other regions of space have grown steadily in terms of number, mass, size, and operational lifetime. In this work we categorize launch traffic by type, mass, and size. GEO traffic is further categorized by operational longitude. Because growth itself defines only the instantaneous environment, we also examine the higher-order derivatives of growth and the effects of fragmentations on the environment.

## 1. INTRODUCTION

The population of man-made satellite objects in orbit about the Earth forms a dynamic environment. Analysts may view this environment in a global sense or on a programmatic basis. The former shall be utilized to portray the global environmental change over the period 1990-2000. The decade's history of fragmentation shall be examined on a programmatic basis to assess the implications for traffic modeling and the future environment.

## 2. LOW EARTH ORBIT (LEO)

Two US Space Surveillance Network (SSN) catalogs form the basis of our comparison. Included are all unclassified cataloged objects in both data sets; a filter was installed to remove objects whose epoch times were older than 30 days. None were removed from either catalog.

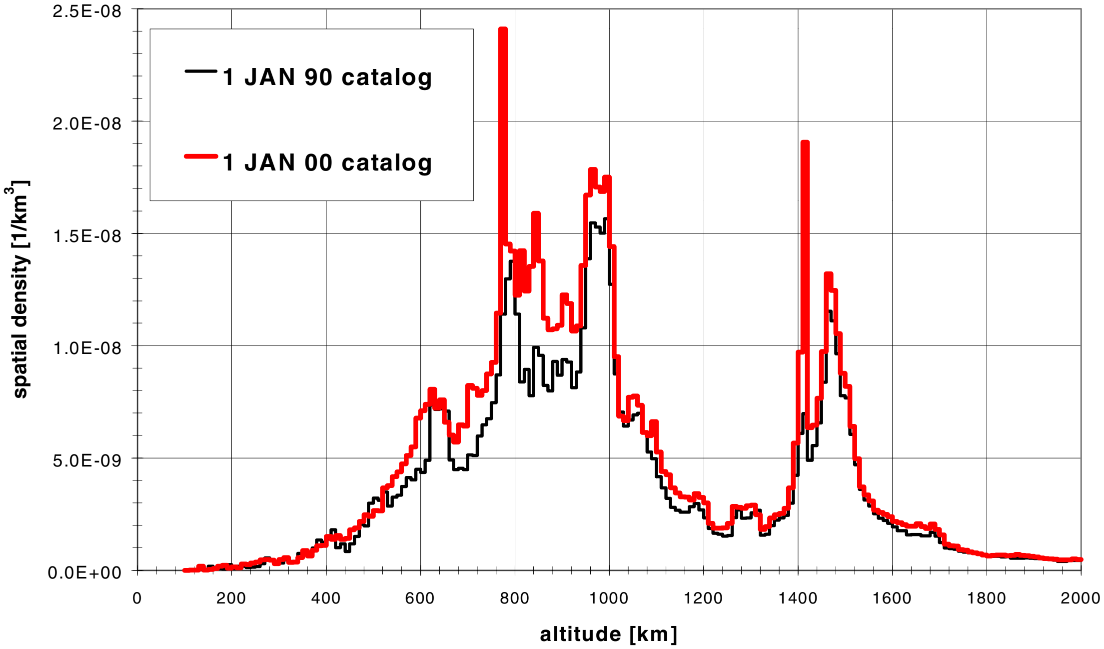

Fig. 1. The LEO spatial density in 1990 and 2000

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Table 1 describes the LEO populations. Of particular interest is the relative growth rates for payloads and rocket bodies versus debris. This is indicative of the effective curbs placed upon debris creation mechanisms. However, it also points out the need to deal effectively with the issue of derelict payloads and rocket bodies, the major reservoirs of both area and mass.

Table 1. The LEO population considered.

| catalog | Payloads & rocket bodies | Debris | Total |
|---|---|---|---|
| 1 Jan 90 | 2063 | 3498 | 5561 |
| 1 Jan 00 | 2769 | 4156 | 6925 |
| % change | 34.22 | 18.81 | 24.53 |

Both catalogs were propagated to a common epoch time using the program SATRAK v. 6. The components of the Salyut 7, Mir, and ISS orbital stations are collected into an aggregate object so as not to depict a plethora of independently-orbiting objects at altitude. Figure 1 depicts the spatial density [1/km$^3$] over the altitude range 100-2000 km and in 10 km altitude bands.

Figure 1 possesses several salient features. Perhaps the most prominent are the “spikes” located between 770-780 and 1410-1420 km altitude. These correspond to the Iridium and Globalstar commercial communication spacecraft constellations, respectively. Under the current end-of-life operations plan, the Iridium constellation would be removed from orbit over one to two years; hence, the spike between 770 and 780 km will disappear unless the constellation is replenished. Less prominent is the Orbcomm commercial constellation, with a primary concentration between 810 and 820 km altitude. Unlike the Iridium constellation, Orbcomm satellites will decay through LEO over approximately 50 years. Smaller constellations also result in local enhancements of the population. For example, the peak between 840-850 km is populated by the Russian Tselina-2 spacecraft constellation, several US Defense Meteorological Support Program (DMSP) spacecraft, and their associated rocket bodies and debris. While the region is traversed by many other space objects, including debris, these satellites and rocket boosters are in near circular orbits. Thus, any constellation of spacecraft whose orbits are tightly maintained are capable of producing a spike similar to that observed with the commercial constellations.

Figures 2 and 3 portray the spatial-density weighted area and mass distributions over the decade. These quantities were weighted to correctly include the effects of elliptical orbits passing through the altitude bins. Both figures include only payloads and associated rocket bodies, since the physical characteristics of operational and fragmentation debris are not well characterized; also, these figures exclude orbital stations as these craft are not representative of space traffic in general.

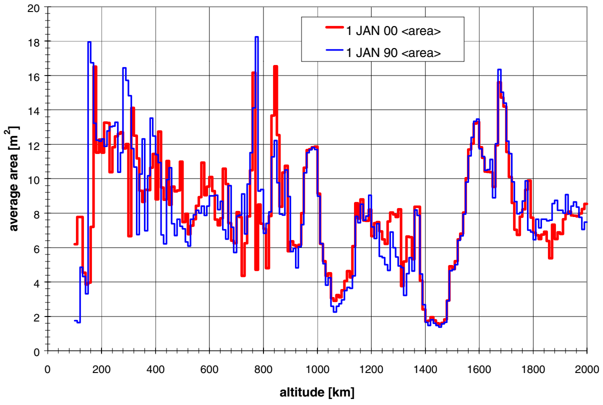

Fig. 2. Area distribution in LEO

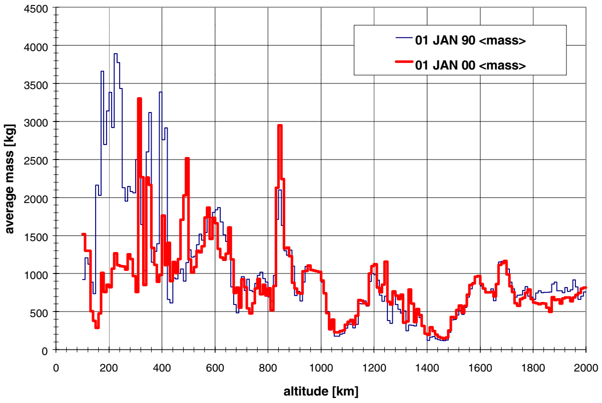

Fig. 3. Mass distribution in LEO

### 2.1 Higher order Behavior

Past efforts to characterize the environment have typically looked only at total population growth over time. A more sophisticated examination considers the rate-of-change as a function of both physical/orbital characteristic(s) and time. These may be termed the velocity, the acceleration, the jerk, and the joust, in common with other areas of physics. The first- and second-order rates in number N are defined by:

$$\dot{N}\left(C_i;t_{j+1}\right) = \frac{N(C_i;t_{j+1}) - N(C_i;t_j)}{t_{j+1} - t_j} \quad (1)$$

$$\ddot{N}\left(C_i;t_{j+1}\right) = \frac{\dot{N}\left(C_i;t_{j+1}\right) - \dot{N}\left(C_i;t_j\right)}{t_{j+1} - t_j} \quad (2)$$

where the $C_i$ is the i$^{th}$ physical or orbital population parameter at time t. The backward difference is appropriate, since the future environment at time has no impact on the environment at time $t_{j+1}$. Third and higher-order rates are generated in an iterative fashion and are evaluated with n+1 temporal snapshots, where n is the order of the rate of change.

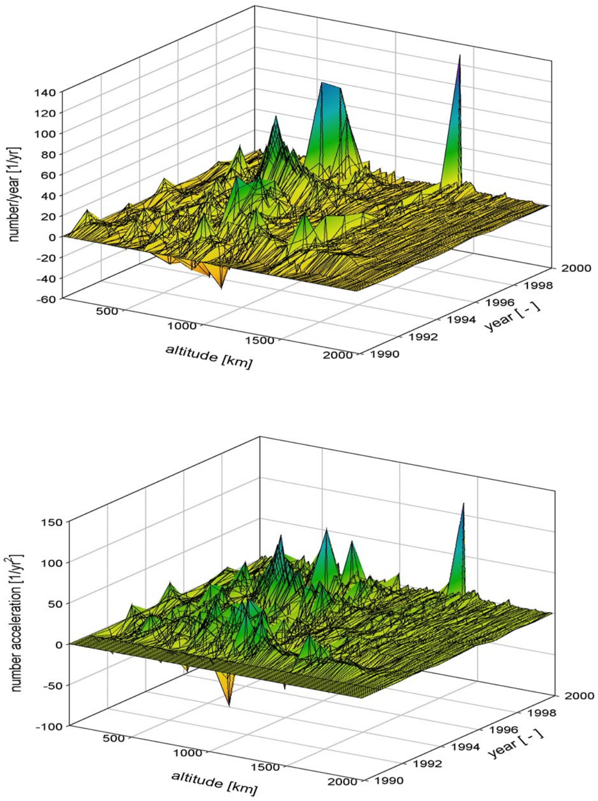

Fig. 4. The LEO number-velocity and acceleration fields

As this figure indicates, the rates of change clearly delineate the areas undergoing change either through enhanced traffic or decay. In the case of the Iridium and Globalstar constellations, two common product cycle (initial deployment, constellation maintenance) trends are evident. This technique has the benefit of portraying the dynamic environment to a higher degree of fidelity as compared to previous one-dimensional models of growth.

## 2.2 Discussion

Not coincidentally, the NASA EVOLVE 4.0 long-term debris evolution computer model predicts that the region between 800 and 1000 km altitude is sensitive to the collision hazard. This result appears driven by the large size and mass of the spacecraft resident there, particularly the Tselina-2 constellation.

Note that both data sets presented are at or near Solar maximum. One may expect the low altitudes (< 600) to increase by up to a factor of two over the next five years, given decreasing Solar activity and assuming the historical fragmentation rate. Such behavior is historically evident when comparing a 1987 SSN catalog with the 1990 data set.

The spatial density chart averages over inclination; hence, collision rates won't be linearly related to the spatial density at any given altitude. Indeed, collision rates will vary not only with the spatial density but also with the inclination-dependent relative velocity. Altitudes dominated by high inclination (70-110°) orbits yield a significantly higher collision rate as compared to those populated by lower inclination orbits. The exception to this general rule returns us to our starting point: the commercial constellations. Because these constellations are maintained in precise orbital planes, their expected collision rate would be versus the "background" population only. Hence, the spikes representing the Iridium and Globalstar constellations do not present the inordinate collision risk implied by a casual examination.

Neither Figure 2 nor 3 exhibit a systematic trend (excepting the altitudes below 500 km in Fig. 3). Both were tested using the $\chi^2$ distribution to assess differences. Differences were not statistically significant at the 95% confidence or 5% level of significance. Perhaps the most dramatic feature is the difference in mass below 500 km between 1990 and 2000. This is due to several low altitude reconnaissance spacecraft (Cosmos 2049 and 2052) and large satellites decaying through the altitude range around 250 km, as well as three functional Electronic Ocean Reconnaissance Satellites (EORSATs, Cosmos 2033, 2046, and 2051) operating at or about 400 km. The deployment of these spacecraft classes has been curtailed over the course of the 1990s, thereby reducing the weighted average mass. Therefore, characterization of space traffic over the past decade and, by extension into the near future, as being fairly constant in mass and area is consistent with historical observation.

## 3. GEOSYNCHRONOUS EARTH ORBIT

The ensemble of payloads and rocket bodies near GEO (nominal altitude of 35786 ± 500 km) was characterized by number, mass, longitude at epoch, and longitudinal drift rate [°/day]. Number, rather than spatial density, was chosen due to low numbers of objects in GEO. Area was not portrayed because the total area was not available for all objects, *e.g.* solar panel area was neglected. Maximum drift rate was limited to ± 1 °/day.

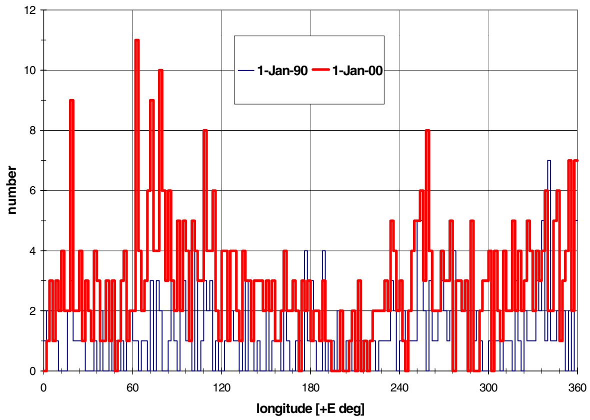

Fig. 5. GEO number distribution

Obvious is not only the overall growth of the GEO population in number, but also the preference for certain orbital slots. Particularly noteworthy is the growth of the population over Asia, the Pacific Rim, and the Americas. Growth in mass is both a function of increasing mass per spacecraft and an increasing number of spacecraft.

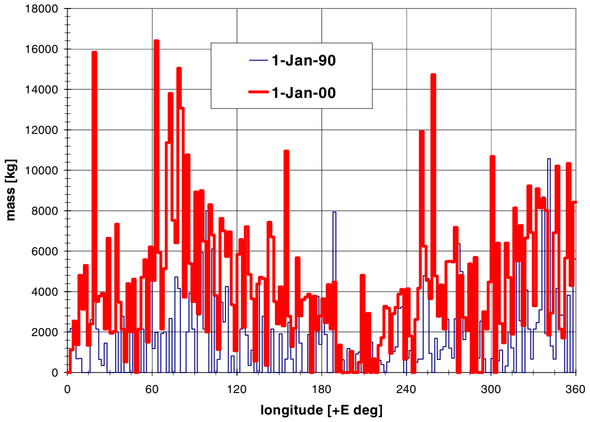

Fig. 6. GEO mass distribution

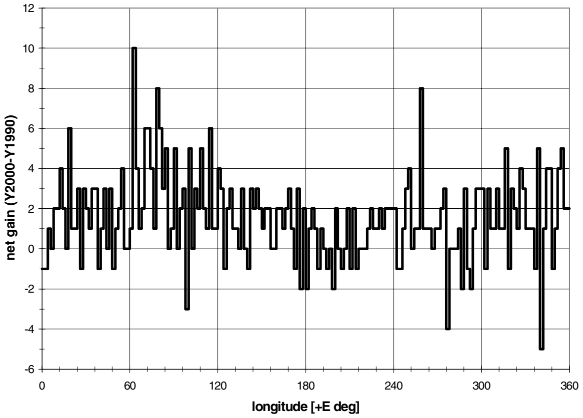

Fig. 7. GEO net loss/gain

## 4. BREAKUPS 1990-2000

Fifty-five explosions, and the first recorded unintentional collision, occurred during the decade. Relative event severity may be gauged from Fig. 8; in this figure, both cataloged and on-orbit fragments (1 January 2000) are presented.

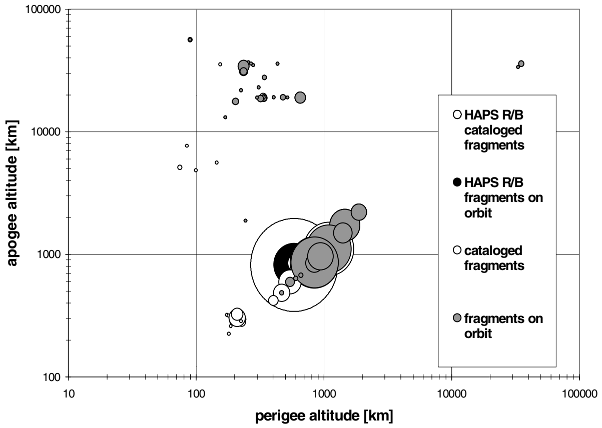

Fig. 8. Fragmentations 1990-2000

Those events producing more than ten (10) cataloged pieces are tabulated below.

Table 2. Major fragmentation events.

| Name | Event date | Cataloged debris |
|---|---|---|
| STEP II R/B | 3-Jun-96 | 703 |
| NIMBUS 6 R/B | 1-May-91 | 237 |
| Cosmos 2227 R/B | 26-Dec-92 | 219 |
| Cosmos 2125-32 R/B | 5-Mar-91 | 86 |
| FENGYUN 1-2 R/B | 4-Oct-90 | 83 |
| Meteor 2-16 R/B | 15-Feb-98 | 68 |
| Cosmos 1484 | 18-Oct-93 | 48 |
| Cosmos 2157-62 R/B | 9-Oct-99 | 34 |
| USA 68 | 1-Dec-90 | 29 |
| Cosmos 2237 R/B | 28-Mar-93 | 29 |
| Cosmos 2238 | 1-Dec-94 | 26 |
| Cosmos 2053 R/B | 18-Apr-99 | 26 |
| RS-15 R/B | 26-Dec-94 | 23 |
| Cosmos 1603 ullage | 5-Sep-92 | 22 |
| Cosmos 2313 | 26-Jun-97 | 13 |
| Telecom 2B – INMARSAT 2 R/B | 21-Apr-93 | 12 |
| Cosmos 1710-12 ullage | 29-Dec-91 | 11 |

The top five events were all rocket body fragmentations. They represent the HAPS, Delta second stage, SL-16 (Zenit) second stage, SL-8 (Cosmos) second stage, and Long March 4 third stage, safe the stage following payload deployment were implemented. The Delta was one of the few remaining on orbit Deltas which was launched (1975) before depletion burns were introduced with Delta 155 in 1981. Two other Deltas (NOAA 2 and Nimbus 5), contemporaries of the Nimbus 6 rocket body, appear unlikely candidates for fragmentation due to only 2-3 kg of fuel remaining onboard [1]. Fragmentation of the Zenit stage was investigated and determined to have been caused by an overpressurization in the propulsion subsystem. A hardware redesign was instituted to prevent repetitions of the Cosmos 2227 and 2237 events. Similarly, Cosmos stages have been identified as experiencing orbital changes while presumably derelict. These changes may be due to outgassing of residual propellants or inadvertent thrusting [2]. The Long March 4 vehicle has been outfitted with venting hardware. This has evidently functioned correctly for one 1999 launch of the vehicle, although a March 2000 fragmentation involved a vehicle in which the venting procedure was implemented. Thus, all of the top five offenders of the decade appear to have had corrective steps taken to reduce the probability of further fragmentation events [3].

Of the remaining 50 explosion events, 16 were assessed as being of unknown cause, seven were the result of a deliberate destruction of the payload, four were assessed as being due to aerodynamic loading, and the balance (23) were propulsion related. Of this latter category, 18 were fragmentations of the SL-12 (Proton) Block D fourth stage SOZ ullage motors. The small motors, used to settle propellants before main engine burns, are typically (but not always) left in GEO transfer orbit. As such, they are difficult to track using the ground-based assets of the US Space Command. While over 100 pieces have been observed by the Space Surveillance Network (SSN) as being associated with a single breakup, as few as one (1) piece and as many as 22 pieces have been formally associated with the breakup of these small objects and entered the catalog. Measures have been taken to eliminate the potential of the SOZ unit to fragment, though the date of implementation of these measures is unknown. The seven deliberate fragmentations featured five members of the so-called sixth generation imaging reconnaissance vehicles, one fourth generation (Yantar) spacecraft, and a Kometa spacecraft. Due to the low orbits utilized by these craft the long term environmental impact of these events is nil.

## 5. IMPLICATIONS FOR TRAFFIC MODELING

Traffic modeling fulfils both economic modeling and debris environmental modeling requirements. In the context of debris modeling, traffic models are required to accurately portray the on-orbit environment. A high fidelity model ensures that orbital, physical, and time dependent environment. Newer environment models require not only apogee and perigee, but also inclination and argument of perigee to perform adequately. Physical parameters include ballistic parameters related to atmospheric drag and an albedo, or similar optical property, to describe the effect of solar radiation pressure. Mission event modeling (or planning) ensures that operational debris are deposited in the proper orbit, that debris released over the lifetime of the mission are accurately incorporated by the model, and that activities as diverse as constellation orbit-keeping, perigee lowering end-of-life maneuvers, replenishment launches, and the maneuvering of the ISS are treated in an efficient, yet robust, manner.

Unfortunately, traffic modeling has traditionally been a weak area [4]. While early versions of long-term environment models utilized a US Space Command catalog of elements and radar cross sections, the increasing sophistication of the NASA EVOLVE model, and the EVOLVE extensions currently being worked upon, require similarly sophisticated input data. While historical traffic is data driven, projections tended to rely upon sketchy information provided by launch agencies or launch contractors, while many government estimates of traffic proved overly sanguine. Thus, a strategy of utilizing a cyclic repetition of recent historical traffic to model the future traffic was adopted, albeit with the certainty that the fidelity of this approach naturally breaks down the further the model is projected into the future.

The present work suggests that this cyclic approach is sufficient to model the general space traffic population in terms of both orbital and physical characteristics. Noted exceptions are provided by commercial communication satellite constellations, *e.g.* Iridium and Globalstar, as well as national assets such as Salyut, Mir, and the ISS.

## 6. CONCLUSIONS

The LEO environment has grown over the last decade. However, growth is insufficient to necessarily boost the probability of collision by a large degree. Rather, the spatial density, relative velocity, and interaction area of the population will determine the collision rate, with mass determining the post-event hazard. While this work did not address the relative velocity distribution (itself a function of target orbit altitude and inclination and insensitive to number of objects), both orbital (spatial density) and physical characteristics (area and mass) of resident space objects were examined. The maintenance of regular constellation orbits, with apogee and perigee being perhaps 10 km different at best in some cases, has been demonstrated to significantly increase the spatial density at certain altitudes and, hence, the collision probability.

Excepting low altitude satellite programs orphaned by political and economic developments, average spacecraft and rocket body area and mass were relatively constant as a function of altitude during the decade. No systematic trends, or statistically significant differences over altitude, were observed. Therefore, differences in collision rate are governed more by orbital characteristics than physical characteristics. Further, space traffic modeling is justified, at least in the near term and excepting one-off programs such as ISS, in using the historical traffic repeated in a cyclic fashion.

GEO exhibits a significant growth both in number of payloads and rocket bodies (currently, only the Proton's Block D stage circularizes its orbit near, though above, the nominal GEO ring population) and in the density of certain preferred orbital slots. The historical traffic directly reflects economic activity, as did the demise or near demise of several low altitude programs.

At the present time, long term environmental modeling using EVOLVE 4 accurately portrays the LEO environment between 800 and 1000 km altitude as being the first orbital region in which to expect accidental collisions. The orbital region between 1400 and 1500 km is modeled as following shortly due to the enhanced spatial density as well as high relative velocities. GEO_EVOLVE 1 portrays the GEO environment as much more benign; however, the crowding of preferred longitudinal slots could significantly increase the modeled collision rate.

## 7. REFERENCES

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