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Utilization Rates of Geostationary Communication Satellites: Models for Loading Dynamics

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The case can be made that a key metric for the commercial space communication sector is the utilization rate, or load factor, of a satellite or a fleet of satellites. In this paper, we first discuss average load factors of fleet of satellites, and then propose that the loading of a single satellite can be modeled as a stochastic process. To illustrate our proposition, we collected and analyzed load factor data of 20 one communication satellites launched between 1980 and late 1990s. We conducted time series analysis and built analytical models for the evolution of utilization rates, or loading dynamics, of a communication satellite. We found consistent results that exhibit three different loading patterns, with a load factor ramp-up, a steady-state load factor during the service life of the satellite, and a decline in load factor after several years of on-orbit service. We further discuss these results and the factors that drive satellite loading dynamics, from the supply/demand (im)balance of on-orbit bandwidth to customer churn from aging transponders and switching towards newer more powerful units. Results should prove useful to satellite operators and industry observers; they also improve the forecast for determining financially optimal satellite design lifetimes.

Nomenclature

$A_{Tx}(t)$	=	number of added transponders during year t
$D_{Tx_{\text{global}}}$	=	global demand for transponders
$f(.)$	=	probability density function
$L(t, i)$	=	load factor of satellite i at time t; also known as the utilization rate or fill rate
$\bar{L}(t)$	=	instantaneous average load factor of $L(t, i)$
$\bar{L}_{\text{EOL}}$	=	end-of-life average load factor of $L(t, i)$
$\bar{L}_{\text{BOL}}$	=	beginning-of-life average load factor of $L(t, i)$
$\langle L\rangle_{\text{global}}$	=	average load factor of the entire geostationary fleet of communications satellite at any given year
$\langle L\rangle_{\text{operator}}$	=	average load factor for the fleet of satellites of a given satellite operator at any given year
$\langle L\rangle_{\text{region}}$	=	average load factor of all satellites serving a given geographical region, e.g., North America, at any given year
$N_{Tx_{\text{total}}}(i)$	=	total number of transponders onboard satellite i
$n_{Tx_{\text{active}}}(t, i)$	=	number of active transponders onboard satellite i at time t
$\langle OC\rangle_{\text{global}}$	=	global overcapacity of satellite transponders
$R_{Tx}(t)$	=	number of retired transponders during year t
$r(t)$	=	range of load factors (min – max values difference) at time t
r_0	=	initial range or dispersion of load factors
$S_{Tx_{\text{global}}}$	=	global supply of transponders
T_{obs}	=	time to obsolescence
α	=	exponential coefficient in the range model
$\Delta D_{Tx}(t)$	=	incremental demand for transponders during year t
$\Delta S_{Tx}(t)$	=	incremental supply of transponders during year t. $\Delta S_{Tx}(t) = A_{Tx}(t) - R_{Tx}(t)$
$\sigma(t)$	=	standard deviation of $L(t, i)$
τ	=	exponential fill time constant

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Introduction

ON 4 October, 1957, a small beeping satellite, Sputnik, heralded the beginning of the space age. From this humble start, the space industry has grown into an impressive $100 billion industry four decades later. Space technology today pervades many aspects of our daily lives with services ranging from video distribution for TV and cable networks, to telephony and data communications, and to Earth monitoring and meteorological services (not to mention the less publicly visible military applications of reconnaissance and electronic surveillance). The commercial space industry unfortunately hit turbulence around the year 2000; its growth potential and financial attractiveness were revised downwards, especially after the collapse of the Low Earth Orbit (LEO) communications systems, which led many companies and investors to revise their commitment to this industry. In 2002, for example, only six communications satellites were ordered, thus severely straining the satellite manufacturers' operations. The number of satellites ordered per year has increased since then, and is expected to range between 8 and 15 for the rest of the decade [1]. Satellites have been rightfully described as the lifeblood of the entire space industry (satellite manufacturers, launch system providers, satellite operators, equipment providers, and space insurance), and the number of satellites ordered per year is to a large extent the defining metric of the industry's level of activity, at least upstream of the space industry value chain (e.g., for the satellite manufacturers and equipment providers).

Another equally important and defining metric downstream in the space industry value chain (e.g., for the satellite operators) is the utilization rate, or load factor, of a satellite or a fleet of satellites. Simply put, a high utilization rate suggests that the demand for on-orbit capacity may not yet be fully satisfied, and the market can absorb additional capacity (hence new satellites will be ordered). Conversely, a low utilization rate suggests that there might be overcapacity in the market, and investment in additional capacity is better put on hold until the market conditions are carefully investigated (or the satellite operator fully loads its on-orbit assets before investing in new ones).

In this study, we set out to explore the loading dynamics of geostationary (GEO) communications satellites. This paper is organized as follows. The following section presents different average load factors of communications satellites, and discusses them as measures of supply and demand (im)balance of on-orbit transponders. Three average load factors are considered: first, $\langle L \rangle_{\text{global}}$; second, $\langle L \rangle_{\text{region}}$, for example North America, Western Europe, or Asia Pacific; and third, $\langle L \rangle_{\text{operator}}$. The discussions in this second section of this paper were supported by data that is either available publicly or reported in the specialized press. Following the "static" analyses of load factors, we turn our attention in the third and fourth sections of this paper to the loading dynamics, not averages but evolution over time of the load factor, of a satellite after it has been launched. We identified a sample of 20-one communications satellites over North America, launched between 1980 and 1997, and collected their yearly load factor from the time of their launch until their retirement. To the best knowledge of the authors, this is the first time such time series data of satellite load factors have been collected, analyzed, and presented to the technical community. The data we collected allowed us to answer three questions. First, how fast does a satellite get "filled up" after it has been launched? Second, does a satellite load factor reach a steady-state level? Third, if a steady-state load factor is reached, does it remain at that level or does it decline (when and how fast if so) as the satellite ages? We found some interesting loading patterns that we report and analyze in this paper. Finally, the last section concludes with the summary and implications of this work.

Satellite Load Factor and Fleet Average Load Factors

The load factor of a communications satellite, also known as its utilization rate or fill rate, is defined as the ratio of the number of transponders active or leased at a given time to the total number of transponders onboard the spacecraft. For a given spacecraft i, its load factor at time t is given by Eq. (1):

$$L(t, i) = \frac{n_{Tx_{\text{active}}}(t, i)}{N_{Tx_{\text{total}}}(i)} \tag{1}$$

Equation (1) represents the "instantaneous" load factor of 1 specific satellite. This measure of the utilization of a satellite payload is rarely available publicly. Instead, the specialized press often reports "average" load factors, for example the average load factor for the entire GEO fleet of communications satellites every year. Figure 1 illustrates this global average. There are, however, different ways of averaging load factors. For example, an average can be calculated for all the satellites serving a given geographical region, e.g., North America or Western Europe, as seen in Fig. 2. Another average load factor can be calculated for the entire fleet of satellites of a given satellite operator as seen in Fig. 3. It is important to note the difference between these average load factors and the instantaneous load factor for one specific satellite given in Eq. (1), the analysis of the latter being the novel contribution in this paper.

Average load factors are important metrics in the commercial satellite communications world. They represent a measure of the supply/demand imbalance of on-orbit transponders, globally or regionally, and reflect to some extent how well satellite operators are managing their on-orbit assets, as we will discuss shortly.

Global Load Factor

Figure 1 shows a steady decline in the average load factor of the entire GEO fleet of communications satellites from 79% in 2000 to 70% in 2003. In 2003, there was globally a total of 7,585 transponders available on-orbit [2]. We refer to this as $S_{Tx_{\text{global}}}$. An average global load factor of 70% (69.85%) indicates that out of the 7,585 transponders available, there were in effect 5,299 transponders in use in 2003. We refer to this number as the global demand for transponders in 2003 $D_{Tx_{\text{global}}}$. The number of unused transponders in 2003 was therefore 2,286. This represents a significant unused on-orbit capacity. Equation (2) relates the global supply and demand of transponders to the global average load factor:

$$\langle L \rangle_{\text{global}} = \frac{D_{Tx_{\text{global}}}}{S_{Tx_{\text{global}}}} \tag{2}$$

Figure 1 also shows a significant drop in global load factor $\langle L \rangle_{\text{global}}$ between 2001 and 2002 from 77% to 71%. This is due to three colluding factors: 1) a significant number of new transponders were launched in 2002 (over 1,000 transponders), 2) few were retired resulting in a net add of 745 transponders in 2002 (compared with 103 net add in 2001), and 3) the demand for additional transponders in 2002 grew at a very slow rate of 2.9% [2]. More generally, we can

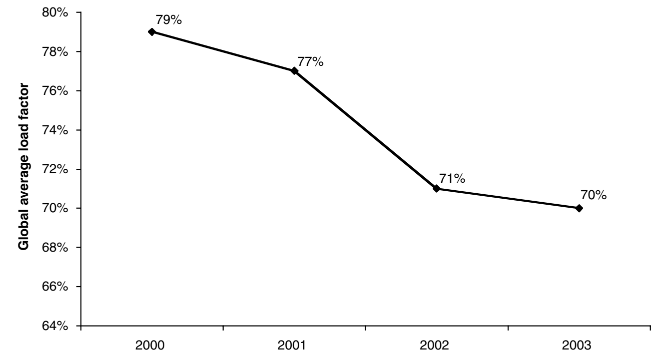

Fig. 1 Average load factor of the entire fleet of GEO communications satellites. Adapted from Ref. [2].

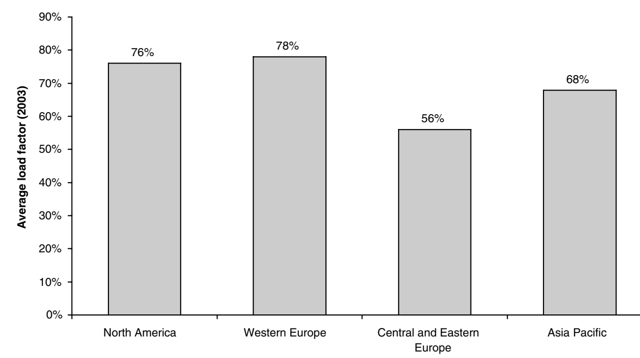

Fig. 2 Average load factor in 2003 by region (Data source: Euroconsult [2]).

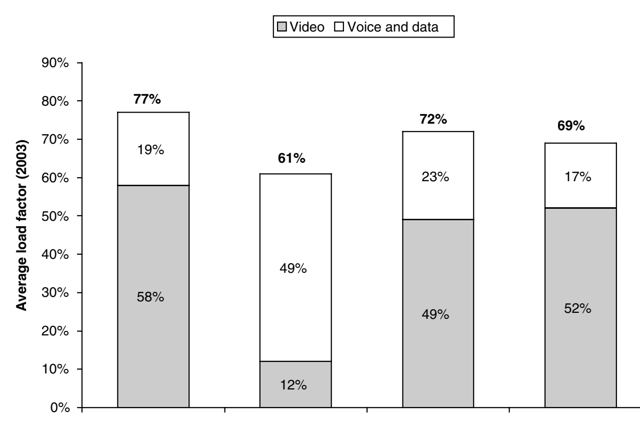

Fig. 3 Average load factor of 4 major satellite operators, and contributions of Video and Voice and Data services to the utilization of their satellite fleet (Data source: Euroconsult [2]).

Table 1 Global supply, demand, and overcapacity in satellite transponders (Data source: Euroconsult [2])

	2000	2003
$S_{Tx_{\text{global}}}$	6,409	7,585
$D_{Tx_{\text{global}}}$	5,072	5,299
$\langle L\rangle_{\text{global}}$	79%	70%
Unused T_x	1,337	2,286
$\langle OC\rangle_{\text{global}}$	21%	30%

relate the global load factor from 1 yr to another by considering the incremental demand for transponders during that year $\Delta D_{Tx}(t)$, and the added and retired transponders during that year $A_{Tx}(t) - R_{Tx}(t)$, as shown in Eq. (3) [the subscript *global* is omitted from Eq. (3) for readability purposes but should be assumed for all the variables]:

$$\langle L(t+1)\rangle = \frac{D_{Tx}(t+1)}{S_{Tx}(t+1)} = \frac{D_{Tx}(t) + \Delta D_{Tx}(t)}{S_{Tx}(t) + [A_{Tx}(t) - R_{Tx}(t)]} \approx \langle L(t)\rangle\left[1 + \frac{\Delta D_{Tx}(t)}{D_{Tx}(t)} - \frac{\Delta S_{Tx}(t)}{S_{Tx}(t)}\right] \tag{3}$$

The approximation in Eq. (3) is valid when the incremental supply of transponders during a year is much smaller than the global supply of transponders, that is $[\Delta S_{Tx}(t)/S_{Tx}(t)] \ll 1$.

The global overcapacity of on-orbit transponders is given by Eq. (4):

$$\langle OC\rangle_{\text{global}} = \frac{S_{Tx_{\text{global}}} - D_{Tx_{\text{global}}}}{S_{Tx_{\text{global}}}} = 1 - \langle L\rangle_{\text{global}} \tag{4}$$

It should be noted that some industry observers consider 20% or less of unused transponders a useful margin to have for reliability purposes (e.g., backup), and to accommodate occasional leases of satellite capacity for unplanned events [2]. While this distinction between unused transponders and overcapacity is pertinent, it can be argued that 20% unused transponders when the global supply is over 7,000 transponders (instead of say a few hundred transponders) is excessive and does constitute "overcapacity." Changes in global transponder supply, demand, overcapacity, and load factors between 2000 and 2003 are summarized in Table 1.

Regional Load Factor

Communications satellites are launched into specific orbital slots and designed to serve specific geographical regions. Regions in turn have different supply/demand characteristics that are not reflected in $\langle L\rangle_{\text{global}}$. This finer level of detail is instead captured in $\langle L\rangle_{\text{region}}$, calculated for all satellites serving a given geographical region . Figure 2 represents this metric for North America, Western Europe, Central and East Europe, and the Asia Pacific region. We see, for example, that the supply/demand imbalance is significantly higher in Central Europe with a load factor of 56% [or conversely an overcapacity of 44% (or $44 - 20\% = 24\%$ based on the definition of overcapacity used in Ref. [2]] than in Northern America where the average load factor is 76% (or 24% overcapacity). Increased overcapacity, along with industry structure and competitive intensity, translates into increased downward pressure on transponders lease prices. For example, the average lease price of a transponder in North America in 2003 averaged \$1.2 million/year, whereas in Central and Eastern Europe, transponder lease price averaged \$0.9 million/year [2].

Operator Load Factor

A third average load factor can be calculated for $\langle L\rangle_{\text{operator}}$. This metric reflects to some extent how well a particular satellite operator is managing its on-orbit assets. Figure 3 shows the load factors of four major satellite operators. Eutelsat, for example, had 77% of its on-orbit capacity leased in 2003, whereas Intelsat had only 61% of its on-orbit capacity utilized during that year (from a total of 1,845 transponders) [2]. This low utilization rate represents a sizable opportunity loss for Intelsat: a simple calculation shows that, at an average lease price of \$1.4 million/year, should Intelast improve its management and operation of its on-orbit assets to the level of Eutelsat (77%), it could generate an additional \$400 million per year. This is a significant revenue increase for a company that generates approximately \$1 billion a year. Figure 3 also shows the contributions of Video and Voice and Data services to the utilization of satellite fleet of each of the four satellite operators we considered. Video is clearly seen as a major contributor to satellite utilization (approximately 50% for three major satellite operators) except for Intelsat, which for historical reasons, being an Inter-Governmental Organization until 2001, had limited strategic flexibility in deciding its service mix of voice and video.

Satellite Loading Dynamics Following Launch

In the previous section, we discussed different average load factors for communications satellites, $\langle L\rangle_{\text{global}}$, $\langle L\rangle_{\text{region}}$, $\langle L\rangle_{\text{operator}}$, from data that is either available publicly or reported in the specialized press. In this section, we are interested in gaining insights into the loading dynamics—not averages but evolution over time of the load factor—of a single satellite i, after it has been launched. $L(t, i)$ can be modeled as a stochastic process or a random function of time. A stochastic process is simply an indexed family of random variables in which the index corresponds to time [3] (in other words, for every specific time t_0, $L(t_0, i)$ is a random variable). We therefore posit that $L(t, i)$ follows some random probability distribution and can be analyzed statistically. When the time index of a stochastic process takes only discrete values, the stochastic process is called a time series. Figure 4 shows the different averages that can be computed for a stochastic process.

To conduct our statistical analysis of $L(t, i)$, we first needed to obtain load factor data of a number of satellites from the time of their launch until their retirement. This information is understandably proprietary and satellite operators are not necessarily eager to publicly share such data, which can be used to target marketing or sales efforts.

To circumvent this difficulty, we teamed with a company that has been tracking and measuring North American transponder usage and supply using their own earth stations of spectrum analyzers in conjunction with a variety of video and audio receivers. The reader is referred to Ref. [4] for a thorough discussion of the data collection methodology. We identified a sample of 20-one communications satellites over North America, launched between 1980 and 1997, and collected their yearly load factor from the time of their launch until their retirement. To the best knowledge of the authors, this is the first time such time series data of satellite load factor is collected, analyzed, and presented to the technical community.

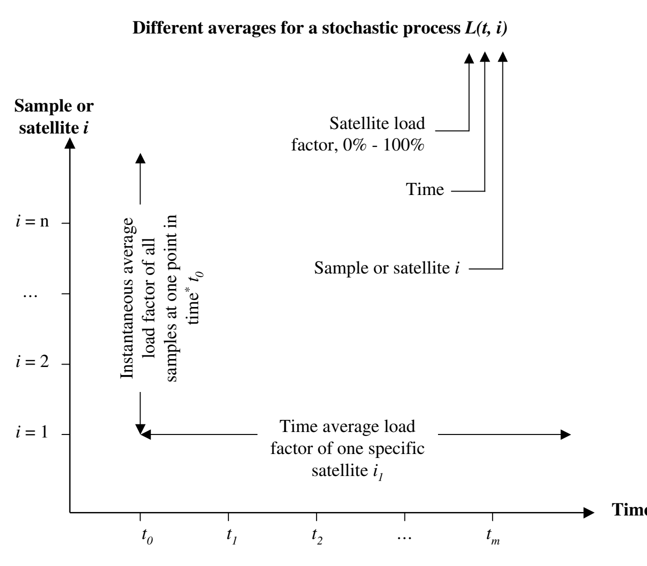

Fig. 4 Modeling satellite load factor as a stochastic process $L(t, i)$.

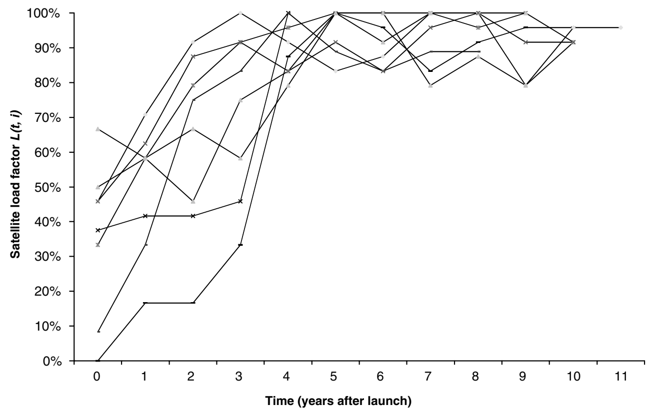

Fig. 5 Load factor raw data for 8 satellites in our sample that were launched in the early 1980s.

An initial display of the raw data collected did not reveal any interesting pattern. However, when we segmented our sample into three categories defined by the launch period of the satellite: early 1980s, late 1980s, and mid-1990s, and initialized the time axis to the year of launch, we found some very interesting patterns in $L(t, i)$. These are discussed in the following section.

Modeling Satellite Loading Dynamics

Of the 21 satellites for which we tracked the transponder usage throughout their design lifetime, eight were launched in the early 1980s, seven were launched in the late 1980s, and six were launched in the mid-1990s. Figure 5 shows the load factor raw data for the first group of satellites launched in the early 1980s. The time axis for all the satellites was initialized to the year of launch.

The data show that a satellite load factor increases after it has been launched, as new customers are acquired and additional transponders are leased. The load factor ramp-up reaches steady state within 3–5 years. Interestingly, we find that some capacity onboard a satellite is already prebooked (before the satellite is launched) and the initial average load factor is not 0% (it is in fact 35% for the sample in Fig. 5). This observation makes business sense and operators ideally should strive to book the entire satellite capacity as soon as or before the spacecraft reaches orbit; failure to do so can be interpreted as an opportunity loss for the operator of the satellite (i.e., an asset or the communications payload in our case is available to generate revenue but it is not put to work).

The instantaneous average load factor (see Fig. 4) is the average at every time step of all the satellite load factors in our sample. It is calculated as follows:

$$\bar{L}(t) = \frac{1}{n}\sum_{i=1}^{n} L(t, i) \tag{5}$$

Based on the previous observations and on a suggestion from Ref. [5], we propose to model $\bar{L}(t)$ as a function of three parameters or degrees of freedom: $\bar{L}_{\mathrm{BOL}}$, $\bar{L}_{\mathrm{EOL}}$, and τ. Equation (6) represents our model structure. Results of the regression analysis using this model are given in Table 2.

$$\bar{L}(t) = \bar{L}_{\mathrm{BOL}} + (\bar{L}_{\mathrm{EOL}} - \bar{L}_{\mathrm{BOL}})(1 - e^{-t/\tau}) \tag{6}$$

In addition to $\bar{L}(t)$, the data collected allow us to model the envelope or range within which the satellites load factors fall for every time step after launch, as we discuss below. Figure 6 shows: 1) the envelope (minimum and maximum values) of the load factor for the satellites in our sample, 2) the observed instantaneous average load factor, and 3) the modeled instantaneous average load factor as given by Eq. (2) and Table 2.

Table 2 Average load factor model parameters for satellites launched in the early 1980s

Model parameter	Value
$\bar{L}_{\mathrm{BOL}}$	35%
$\bar{L}_{\mathrm{EOL}}$	95%
τ	2.5 yr
R^2	0.95

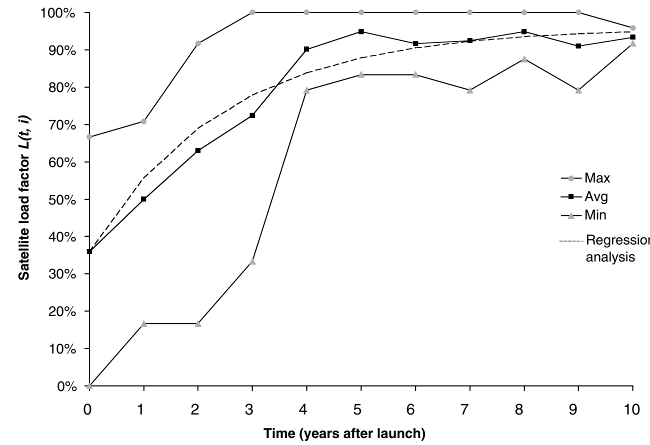

Fig. 6 Load factor (average, min – max, and regression analysis) for 8 satellites in our sample that were launched in the early 1980s.

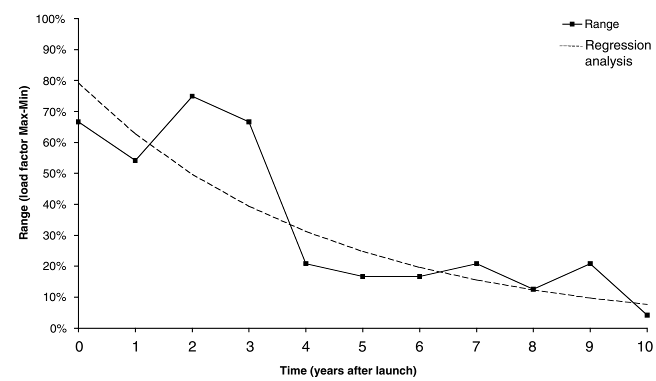

Fig. 7 Dispersion or range of load factors (min – max difference) for satellites launched in the early 1980s.

We observe, for example, on Fig. 6 an initial large dispersion of load factors right after launch ($\bar{L}_{\mathrm{BOL}}$ varies from 0% to 67%, and has an average of 35%). This may reflect how aggressive a satellite operator has been in prebooking capacity onboard its satellite before launch: a satellite with an initial load factor of 0% suggests the satellite operator has either delayed or not been successful in its sales and marketing effort before its on-orbit asset was launched and became operational. On the other hand, a communications satellite with a high initial load factor suggests either that the operator has been aggressive and successful in its sales efforts before the launch of the spacecraft, or that the spacecraft is in fact a "replacement satellite" taking overcapacity from another satellite that has reached the end of its service life. This latter hypothesis will be further discussed later.

We also observe on Fig. 6 that the dispersion of the load factor at every time step narrows down with time and reaches almost a steady state within 4 years. The range, or difference between the minimum and maximum values, in the load factors for satellites launched in the early 1980s is represented in Fig. 7. The narrowing of this range may be attributed to the fact that all satellite operators become with time equally aggressive and effective in booking their on-orbit assets.

We propose to model this range $r(t)$ with a decreasing exponential function of time. Equation (7) represents our model structure (also shown in Fig. 7).

$$r(t) = r_0 e^{-\alpha t} \tag{7}$$

Results of the regression analysis using this model are given in Table 3. For simplification, we assume that the range is symmetrical with respect to the sample mean. By doing so, we make an average

Table 3 Model parameters for the range of load factors [Eq. (7)] for satellites launched in the early 1980s

Model parameter	Value
r_0	79%
α	0.23
R^2	0.71

Table 4 Summary of the model parameters for the load factor [Eq. (8)]

Model parameter	Value
$\bar{L}_{\mathrm{BOL}}$	35%
$\bar{L}_{\mathrm{EOL}}$	95%
τ	2.5 yr
r_0	79%
α	0.23 yr^{-1}

error of 18% on the minimum and maximum values of the load factors at each time step for the satellites in our sample (alternatively, we could provide a parametric model for the minimum or maximum values of the load factor).

Finally, although the data we collected are insufficient to confirm the following (our sample space is too small to prove the following statistical inference), we *hypothesize* that $L(t, i)$ is normally distributed, i.e., it has a Gaussian probability density function at each time step, and that the dispersion of load factors we observed in Fig. 6 and 7 represents 95% of all possible measurements. In other words, we assume that the range $r(t)$ represents 4 standard deviations (for a normally distributed random variable x, 95.4% of all measurements fall within the mean plus or minus 2 standard deviations ($\mu_x \pm 2\sigma_x$), of our assumed random vector $L(t, i)$. The Gaussian distribution we consider for $L(t, i)$ is truncated and confined to the values of L between 0% and 100%. We translate this hypothesis mathematically as follows (the values of the parameters are summarized in Table 4):

$$\begin{cases} f[L(t)] = \frac{1}{\sigma(t)\sqrt{2\pi}}\exp\left\{-\frac{[L(t)-\bar{L}(t)]^2}{2[\sigma(t)]^2}\right\} & \text{for } 0\% \le L \le 100\% \\ \bar{L}(t) = \bar{L}_{\mathrm{BOL}} + (\bar{L}_{\mathrm{EOL}} - \bar{L}_{\mathrm{BOL}})(1 - e^{-t/\tau}) \\ \sigma(t) = \frac{r(t)}{4} = \frac{r_0}{4}e^{-\alpha t} \end{cases} \tag{8}$$

Load Factors of Satellites Launched in the Late 1980s

We now turn our attention to the second group of satellites in our sample. These satellites were launched in the late 1980s. As mentioned previously, we tracked transponder usage of 20-one satellites throughout their design lifetime: eight of these were launched in the early 1980s, seven were launched in the late 1980s, and six were launched in the mid-1990s.

Figure 8 shows: 1) the envelope (minimum and maximum values) of the load factor for the satellites in this second group of our sample, 2) the observed instantaneous average load factor, and 3) the modeled instantaneous average load factor as given by Eq. (9).

The fundamental difference in the loading dynamics between the satellites in our sample that were launched in the early 1980s (previous subsection) and those launched in the late 1980s is the absence of a ramp-up phase in the latter, as seen in comparing Figs. 6 and 8. In other words, the sampled satellites that were launched in the late 1980s start with an initially high load factor ($\bar{L}_{\mathrm{BOL}} = 95\%$) and their load factor remains relatively constant through their design lifetime ($\bar{L}_{\mathrm{BOL}} = \bar{L}_{\mathrm{EOL}}$); whereas the sampled satellites that were launched in the early 1980s start with a lower load factor ($\bar{L}_{\mathrm{BOL}} = 35\%$), then exhibit a fill process and take between three to 5 years before their load factor reaches a steady-state (Fig. 6).

Two reasons can explain this difference in the loading dynamics between these two groups of satellites in our sample: 1) by the late 1980s, satellite operators had determined from their past experience how to aggressively prebook capacity onboard their satellites before launch and realized the quantifiable financial advantages of doing so,

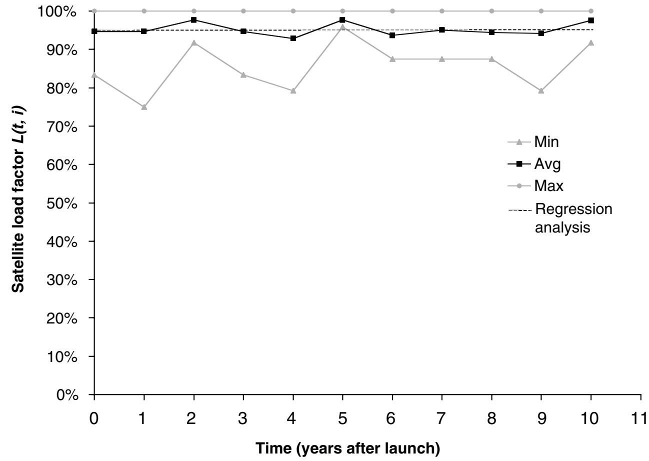

Fig. 8 Load factor (average, min – max, and regression analysis) for 7 satellites in our sample that were launched in the late 1980s.

or 2) most satellites launched in the late 1980s are simply "replacement satellites" taking overcapacity from other satellites that are considerably loaded but have reached the end of their service life. If the retiring and replacement satellites have identical capacity, then the beginning-of-life load factor of the replacement satellite will be equal to the end-of-life load factor of the retiring satellite. Otherwise, if the two satellites' capacities differ, we will observe a discontinuity in the L_{EOL} of the retiring satellite and the L_{BOL} of the replacement satellite.

We propose to model the instantaneous average load factor of the satellites in our sample that were launched in the late 1980s (Fig. 8) as a constant. Also, for simplification, we assume that the range or dispersion of $L(t, i)$ around the mean $\bar{L}$ is symmetrical with respect to the sample mean. By doing so, we make an average error of 8% on the minimum values of the load factors at each time step for this second group of satellites our sample. Mathematically, we write this trivial model as follows:

$$\begin{cases} \bar{L}(t) = \bar{L}_{\mathrm{BOL}} & = 95\% \\ r(t) = r_0 & = 5\% \end{cases} \tag{9}$$

Load Factors of Satellites Launched in the Mid-1990s

We now turn our attention to the third and last group of satellites in our sample. This group consists of six satellites launched in the mid-1990s. Figure 9 shows: 1) the envelope (minimum and maximum values) of the load factor for the satellites in this third group of our sample, 2) the observed instantaneous average load factor, and 3) the modeled instantaneous average load factor as given by Eq. (10).

We first observe on Fig. 9 that satellites launched in the mid-1990s in our sample start with an initially high load factor ($\bar{L}_{\mathrm{BOL}} = 95\%$), just as we saw previously on Fig. 8 for the satellites launched in the late 1980s. The same previous interpretation or explanation applies, namely that this reflects either the fact that these satellites are replacement satellites, or that satellite operators are now routinely prebooking most of the capacity onboard their satellites before their launch.

Figure 9 shows, however, one striking difference with all previous load factor dynamics, namely that satellites exhibit a decrease in their load factor after 5–7 years of operations. This observation will be of significant importance if it is a common loading pattern to all communications satellites launched over the last decade. We discuss the implications of this observation in the Conclusion. Unfortunately, given the small size of our sample and some of the problems with the data that we have, for example one satellite in our sample failed after 7 years of operations, which we can see on Fig. 9, and thus significantly distorted the averages, we cannot confirm this loading pattern. If that failed satellite were not included in the data set, we would still observe the decrease in the load factor and nothing would be different up until year 6 of operations; the difference, however, would be with a different lower envelope of the load factor

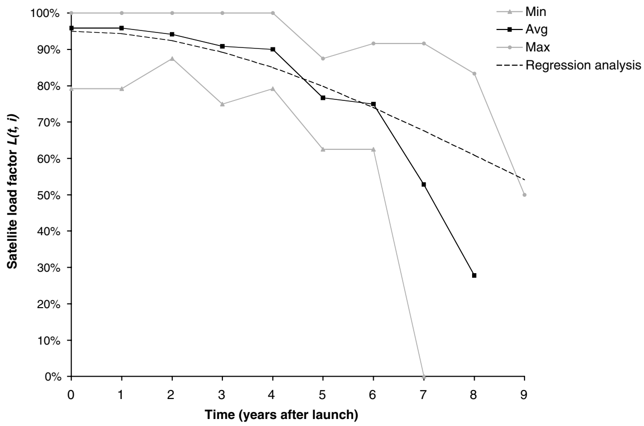

Fig. 9 Load factor (average, min – max, and regression analysis) for 6 satellites in our sample that were launched in the mid-1990s.

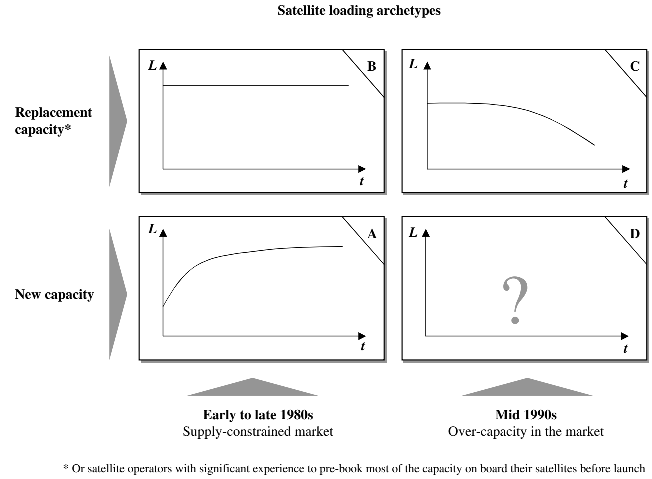

Fig. 10 Satellite loading dynamics: four archetypes classified across two dimensions, type of capacity launched, and supply/demand (im) balance in the market.

as seen on Fig. 9 (labeled *Min* on the figure) after year 6. This in turn would slightly modify the parameter, We discuss next T_{obs} in the model from 12 to 12.8 years. We can instead hypothesize that if this loading pattern is confirmed, it may correspond to end users of satellite capacity turning away from "aging" transponders and switching towards newer more powerful and reliable units. This hypothesis is plausible given that there has recently been an increasing oversupply of transponders (on-orbit capacity is becoming increasingly commoditized), and end users have significantly more choice and market power than in the past to "shop around" for newer, better, and cheaper transponders.

We propose to model the instantaneous average load factor of the satellites in our sample that were launched in the mid-1990s (Fig. 9) as a decreasing function of time with two parameters or degrees of freedom: an initial $\bar{L}_{\mathrm{BOL}}$ and a T_{obs}, as shown in our model structure in Eq. (10).

$$\bar{L}(t) = \bar{L}_{\mathrm{BOL}} \mathrm{e}^{-(t/T_{\mathrm{obs}})^2} \tag{10}$$

Such model structure is often used to model the sales of a component as it goes through its life-cycle phases of maturity, saturation, then decline and phaseout. The reader is referred to [6,7] for a more elaborate discussion of this model's rationale and assumptions. Parameters of the regression analysis using this model are given in Table 5.

The range of the data we collected for the load factors of satellites launched in the mid-1990s (before the one satellite failure occurred as seen on Fig. 9) falls within $\pm 15\%$ of instantaneous average load factor model given in Eq. (10) and Table 5. Unfortunately, the quality of the data for this group of satellites does not warrant that we further model this range as we did with the two previous groups of satellites in our sample.

Summary of Satellite Loading Dynamics: Four Archetypes

Based on our previous discussion and data analyses, we propose four archetypes for satellite loading dynamics. These archetypes are classified based on two dimensions: the type of capacity launched, whether it is a new or replacement satellite; and the market conditions, whether the market is supply constrained (i.e., the demand can absorb any capacity that is provided) or whether there is overcapacity in the market. These four archetypes are represented in Fig. 10.

Table 5 Model parameters for the average load factor [Eq. (10)] of satellites launched in the mid-1990s

Model parameter	Value
$\bar{L}_{\mathrm{BOL}}$	95%
T_{obs}	12 yr
R^2	0.84

Archetype A

This archetype or satellite loading pattern corresponds to what we observed with the first group of satellites in our sample (Figs. 5 and 6), namely an initial ramp-up phase of the load factor followed by a steady-state phase that remains throughout the operational life of the satellite. The satellite load factor increases after launch as new customers are acquired an additional transponders are leased. The steady-state phase is maintained throughout the operational life of the satellite, as the demand for on-orbit capacity remains unmet (supply-constrained market).

Archetype B

This archetype corresponds to what we observed with the second group of satellites in our sample (Fig. 8), namely a relatively constant load factor throughout the operational life of the satellite (absence of a ramp-up phase). Satellites that exhibit such loading dynamics are replacement satellites taking overcapacity from other satellites that are considerably booked but have reached the end of their service life.

Archetype C

This archetype corresponds to what we observed with the third group of satellites in our sample (Fig. 9), namely a steady-state phase with a relatively high beginning-of-life load factor (again with an absence of a ramp-up phase as with archetype B), followed by a decline phase or a decrease in the load after several years of operations. This loading pattern is proposed for replacement satellites that are launched to serve a market that is oversupplied with on-orbit capacity, and customers can turn away from aging transponders and switch towards newer more powerful and reliable units.

Archetype D

Although we did not observe this loading pattern in our data, we can hypothesize the existence of such loading dynamics for a "new" satellite (i.e., not a replacement satellite) that is launched to serve a market oversupplied with on-orbit capacity. This archetype therefore has an initial ramp-up phase, a steady-state phase, and a decline phase.

Conclusions

In this paper, we set out to explore the loading dynamics of geostationary communications satellites. We began by presenting different average load factors of a fleet of satellites, and considered them as measures of supply and demand (im)balance of on-orbit transponders. Following these static analyses of load factors, we turned our attention to the loading dynamics (not averages but evolution over time of the load factor) of a satellite after it has been launched. We proposed that the loading of a single satellite can be modeled as a stochastic process. To illustrate our proposition, we collected and analyzed yearly load factor data of 20-one communication satellites launched between 1980 and late 1990s over North America. The data we collected allowed us to answer three questions. First, how fast does a satellite get "filled up" after it has been launched? Second, does a satellite load factor reach a steady-state level? Third, if a steady-state load factor is reached, does it remain at that level or does it decline (when and how fast if so) as the satellite ages? We found and modeled three different loading patterns that are consistent within groups of satellites launched in the early 1980s, in the late 1980s, and in the mid-1990s (load factor ramp-up in 3–4 years; a steady-state load factor between 80 and 100%; and a decline in load factor after 5–7 years on-orbit for satellites launched in the mid-1990s). Based on these findings, we proposed four archetypes or loading dynamics patterns that we classified based on two dimensions: the type of capacity launched, whether it is a new or replacement satellite; and the market conditions, whether the market is supply-constrained or whether there is overcapacity in the market. The loading pattern with a decline phase is proposed for satellites that are launched to serve a market that is oversupplied with on-orbit capacity, and customers can turn away from aging transponders and switch towards newer more powerful, reliable, and cheaper units. If this loading pattern were confirmed for the entire fleet of communications satellites (not just the ones in our sample), it would entail a significant design implication: that satellites with shorter design lifetime (e.g., 10–12 years) may be financially better than the current 15 years life for communications satellites [8].

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