Why is bigger better?

From our communications consultant Walter L Morgan

The cost per transponder decreases sharply as the number of transponders per satellite is increased

Space business deals in facts, so to test the perception that larger geostationary satellites are more economical and therefore will dominate future designs, we collected together the cost to build, launch and initially insure a large number of commercial telecommunications satellites. Based on actual data, we conclude that the concept is clearly correct. There are no immediate reasons to expect that this trend will not continue until the full capabilities of the launch vehicles are reached. Since launchers are also growing, this trend should continue into the immediate future.

It is shown that the cost per transponder decreases sharply as the number of transponders per satellite is increased. Does this mean that eventually only the large operators (that are capable of fully utilizing this economy of scale) will survive? In an environment of dropping transponder costs (to the operator) and nearly stable transponder lease charges (fueled by increasing demand), it is no wonder that many operators are reporting double-digit profit percentages. It appears that this happy situation can continue or even get better as new forms of transponder uses (Internet, HDTV, etc) emerge as results of technology inversion and economy of scale.

Technology inversion is based on identifying a key item (in this case the satellite) and doing everything possible to reduce the cost and operating complexity of thousands of end user devices (Earth stations). This has already been done with direct-to-home digital TV and is coming for satellite Internet, multimedia broadband and other services. To simplify the Earth segment, the satellites are getting larger and more capable. At the same time the economy of scale is reducing the cost, thus allowing consideration of advanced characteristics to fuel the technology inversion principle. This makes the cost of the single central item (the satellite) more expensive in the hope that the number of new customers (hence transponder demand) and revenues will explode.

This paper quantifies this evolution that is bordering on an economic revolution. The reduced costs are taking satellites into new consumer mass markets that have vast revenue potentials. It reviews the history of how we have gotten to what we consider big satellites. The future will favor still larger satellites.

Theory of the economy of scale

As more capacity is added to a satellite, the operating costs decrease on a per transponder basis. In addition, the initial cost per transponder for construction, launch and insurance drops. Figure 1 (p12) is based on a collection of satellite characteristics at the Communications Center. This covers a wide range of satellites launched over the last 15 years and those currently in production. To make the data comparable, the costs of earlier satellites have been inflated to 1999 dollars. This figure applies to the conventional fixed satellite services (FSS) and a few large (16 to 32 transponder) BSS satellites. Satellites with only a few transponders (BSS, MSS and digital audio) have been excluded to make the comparison credible.

As expected, there is data scatter (not all transponders are created equal due to choices in power, bandwidth, etc) but the trend line is clear. Going from 12 to 24 transponders cuts the cost per transponder by 30 percent. Doubling to 48 transponders cuts the average cost again by more than half. In general, the transponders on the large satellites are much more capable than those on the older satellites with fewer transponders. This is a case of better capacity costing less. In the meantime, the lease charges for transponders have been slowly increasing.

By adding more capacity at a single orbit location, a specialized 'neighborhood' can be created. Some locations (eg, 19° East) contain a smorgasbord of video channels and are like the Broadway of entertainment. Others concentrate on business services (data, business video, etc) and others on TV networks or education. Eventually small office/home office (SOHO) and Internet locations may evolve. By increasing the quantity of these specialized services,

➡

Why is bigger better?

these locations can command premium transponder lease rates and have stable fill factors. Thus, while unit costs are dropping, the profit margins can disproportionately increase. A properly planned big satellite can be much more attractive than operating a fleet of smaller satellites at that location.

How do initial costs change with size?

Figure 2 (p12) compares the cost per satellite versus the mass launched. The dollar amounts include the satellite, launch and the insurance inflated to 1999 dollars. A 2.5 ton satellite costs about US$200 million in orbit. If the mass is doubled (to 5 tons or 11,000 pounds), the cost goes to about US$300 million (an increase of only 50 percent). As the scatter shows, these are only average costs.

Why do costs vary?

Commercial communications satellites consist of two major portions:

a) The telecommunications transponders. We refer to this as the payload because its sole function is to be leased (or sold) in units of transponders. This is the revenue-producing part of the satellite, hence the use of the term Apay@; and

b) The bus or housekeeping portion. The function of this part is to support the payload, even though it generates no revenue on its own. It is like a business overhead.

The bus consists of power generation and storage, the station-keeping and attitude control, the thermal control, the structure and the telemetry, tracking and control subsystems. As spacecraft get larger, the payload mass tends to grow substantially while the bus may grow very slowly. In other businesses, we would say that the revenues grow faster than the overhead. This is a recipe for success.

What happens when capacity is doubled?

US communications satellites started with 12 transponders at C-band with five to eight watt power amplifiers. These used the Hughes HS-333 bus. The bus mass (excluding the share of the power supply needed for the payload) accounted for about two thirds of the total dry mass of the satellites.

The next generation had 24 transponders with eight to 17 watt transponders. The following generation had both C- and Ku-band with the equivalent of 48 transponders. By this time, the bus mass had dropped below 50 percent. In part, this was due to the switch from spinning satellites (that had two structures) to the more efficient body stabilized design and the use of improved power subsystems. The new HS-702, Loral 20-20, Lockheed Martin A-2100, Alcatel Spacebus and Matra Marconi Eurostar designs continue this evolutionary trend. At the same time, the launch vehicle manufacturers keep offering larger vehicles, like the Ariane V.

What metrics are used?

Each manufacturer or operator will select a metric that emphasizes its system performance. Among the choices are:

- Dollars per transponder (see Figure 1)
- Dollars per kg mass (see Figure 2, p12)
- Dollars per DC watt at end of life
- Dollars per RF watt (total power into the antennas, see Figure 3, p13)
- Dollars per MHz (bandwidth in MHz)
- Dollars per radiated power (expressed in watts, not dBW)
- Dollars per radiated power x bandwidth (Watt MHz)

Of these, we prefer the first because it is most closely related to revenues and therefore profits. Since transponder bandwidths are not uniform (with 25 to 54 MHz being common), this is an imperfect metric, but better than the unrealistic use of 36 MHz equivalents. Transponder rates do not change linearly as the power or bandwidth is changed, thus a 72 MHz transponder is not twice as valuable as one at 36 MHz. In some areas of the world, performance and prices seem to be disconnected, thus the cost per transponder may be the most practical metric, especially for operators and investors. The alternative metrics are of interest to engineers and manufacturers.

Are bigger satellites for everyone?

No, just like airlines, different operators have differing needs for capacity. Boeing, for instance, still makes the 737 and 747 series which represent the market extremes. Others make smaller aircraft and larger-than 747 craft are in study. In the same way, Hughes offers the 24 transponder HS-376, the 48 transponder HS-601 and now the still larger HS-702 series. Others, like Spacebus, offer a range of bus designs (900 to 6000 kg and 1.5 to 20 kilowatts).

As in the case of airlines, one size will not fit all cases. A 747 may be very efficient for long-haul routes with high fill factors, but the operating costs would doom most short haul and low fill factor operators.

The lower initial cost per transponder may encourage operators to buy more capacity than immediately needed, but only if there is sufficient spectra available and a reasonable expectation that the extra capacity can be leased by the end of life. Since going from one satellite size and launch vehicle size to the next (eg, HS-376 to HS-601 class) is done as a step in costs, this decision requires careful study.

A single large satellite with

After decades of promises, electric ion propulsion is reality. This offers the hope of decreasing the station-keeping subsystem (including fuel) at least by a factor of two

multiple, non-overlapping, beams could be shared among several operators. The Sirius-2 satellite shared by GE Capital and the Swedish Space Corporation is an example.

Are there limits on size?

The major limitations are the launcher mass capabilities, the dimensions of the launcher shroud and the ability to generate power and to dump excess heat into outer space. The fuel needed to maintain a geostationary satellite stationary presently consumes a large portion of the bus mass.

The power supply growth has been enabled by efficiency improvements in solar cells and batteries. It is expected that by 2002 a square meter of solar cells will be able to generate twice as much power as today. The fuel and the associated thrusters required to keep a satellite in position have improved.

Finally, after decades of promises, electric(ion) propulsion is reality. This offers the hope of decreasing the station-keeping subsystem (including fuel) at least by a factor of two. Alternatively, the station-keeping life can be doubled (from 15 to 30 years). In reality, a lighter, longer life (perhaps 18 to 20 years) compromise will be made.

Solar collectors, swing-out thermal radiators, active thermal controls, movable antennas, etc all add complexity and potential new failure modes, but they make bigger satellites possible.

There is an obvious concern over placing too many of the operator's customers on a single satellite, especially one with lots of things that could go wrong. So far, this does not seem to be slowing growth, even after Galaxy IV. Are two smaller satellites better, even if they are not as cost competitive, or does this just double the odds that one will be lost?

Table 1 Multibeam RF Power Requirements

Beams	**N=1**	**N=100**
Per Beam Power (radiated EIRP, dBW)	50	50
Per Beam Power (radiated watts)	100,000	100,000
Antenna gain (dBi or ratio)	30 dBi, 1,000:1	50 dBi, 100,000:1
Antenna gain (ratio to N=1 case)	1:1	100:1
RF power needed per beam (to get 100,000 watts of EIRP), watts	100	1
Number of beams to cover area (N)	1	100
Total RF Power (watts)	**100**	**100**

New payload configurations vs size?

Traditionally, most domestic commercial communications satellites have used 'bent pipe' transponders and a single uplink/downlink beam. The only frequency reuse is dual polarization which turns 500 MHz into 1,000 MHz (less guard bands that reduces the 1,000 to 864 MHz). This allows for 24 transponders at 36 MHz (or other combinations that total approximately 864 MHz).

International satellites (like Intelsat, New Skies, PanAmSat and Loral Orion) may have multiple beams. Provided the beams do not overlap, additional frequency reuse is possible. Two beams could yield 48 transponders per band. Three could be serviced by 72 transponders, etc This paves the way to larger satellites.

Multibeam satellites

Future satellites may subdivide their service area into small beam coverage areas. Because some beam overlap is needed to avoid gaps in the coverage, using N beams (where N may be a large number like 100 or so) will

➡

Why is bigger better?

result in a large frequency reuse, but substantially less than N.

The basic reason for N beams is to increase the satellite's uplink sensitivity and its radiated downlink power. These permit smaller (lower cost) Earth stations and/or higher data speeds.

The N beams generally bring with them the need to connect any uplink beam to any other downlink beam. The satellite needs an on-board computer-controlled telephone office-like switch to connect these beams. Regeneration of the signals as they pass through the satellite also adds value, but at the expense of added mass.

It is fortunate that the economy of scale in the bus has driven the cost of this added mass to the point where it becomes reasonable to consider on-board processing.

Mass per transponders

Two types of satellite power amplifiers are used: traveling wave tube amplifiers (1.5 to 20 GHz and beyond) and solid state power amplifiers (137 MHz to 12.75 GHz). For the same radio frequency (rf) power output, the TWTAs are heavier but take less dc power than the SSPAs.

To cover a given area (for example, Europe), subdividing the area into N beams allows substitution of antenna gain for brute force power amplifier power. See Table 1, p11.

In this simplistic example, we have assumed all parts of an area need the same bandwidth. In reality, there will be some high and many low traffic areas.

The model shows that a spot beam providing 1/100th the area of the single wide area beam only needs a very small power amplifier output (1/100th). If all 100 beams had to be simultaneously powered, the total rf power would be the same as a single beam (100 watts in this example). In reality, 100 very low power TWTAs will far outweigh 100 SSPA, be much larger, but may consume less dc power. With the low cost of dc power (in terms of mass and dollars), any penalty is readily accepted. The single 100 watt TWTA is heavier than 100 little SSPAs. The catch of this approach is the extra equipment needed. This includes:

- The multi-beam antenna mass to produce the N beams;
- The antenna beam forming networks;
- The beam switches or power-steering matrix;
- Any on-board processing;
- The redundancy switches, cables, etc

Basically, mass is moved out of the active amplifiers into the above parts that are primarily passive mechanical items. Under the right combinations, the total payload mass decreases as the number of transponders increases. This potential was identified years ago but is only now being used.

In reality, non-broadcast applications will not simultaneously need the same information at the same time in all N beams. This allows time-sharing a more limited number of power amplifiers by steering power only to the active beams. This is much more power- mass- and cost-efficient. It eliminates wasted power into inactive beams. This also reduces beam-to-beam and satellite-to-satellite interference. Using power steering reduces the payload mass, but leads to capacity limits. In the immediate future, this technology will be used for the Ka-band and mobile satellites but can be extended into other bands.

In reality, most satellites will take as many of these efficiencies and will load on as much communications as possible without overloading the selected launch vehicle.

How will more efficient bus designs be used?

As indicated in the opening, there are two parts to any satellite: the payload and the bus. Assuming the total mass is constant, any efficiencies in the bus will flow directly to the payload. This extra mass can be used to increase the redundancy (by adding more spare parts), to add more transponders, new frequency bands, more beams, on-board processing, etc. Since

Fig 1 Average cost per transponder (US$ 1999)

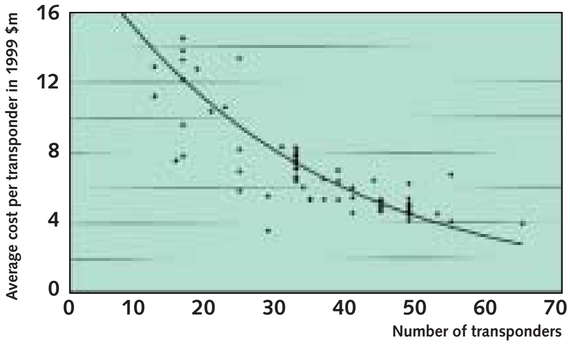
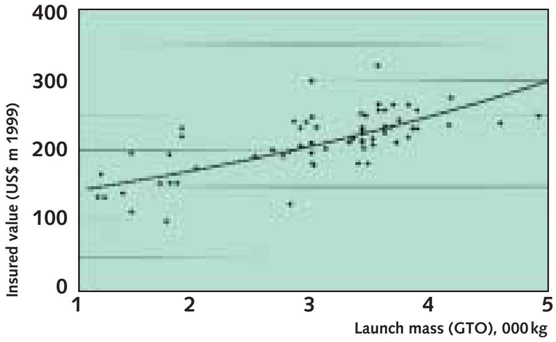


Fig 2 Price as a function of launched mass (US$ 1999)



Future satellites may subdivide their service area into small beam coverage areas

the reliability of the payload is already high and, in general, adequate spare active parts are already carried, there is a strong motivation to add transponders and expand the coverage of services provided.

Increased rf power needs

With the emergence of the 45 to 60 cm direct-to-home antennas, the demand for high rf power satellites has increased thus requiring larger, more powerful satellites.

New frequencies

Most existing satellites are based on using 500 MHz of spectrum. Some of the newer satellites make use of the expansion bands that add 300 MHz at C-band and up to 500 MHz at Ku-band. Assuming coordination is possible, this adds additional transponder capacity, thus extending even a single beam (N=1) dual band satellite from 48 to 67 potential transponders. SBi

Fig 3 RF power vs insured value (US$ 1999)