Allocation of Orbit and Spectrum Resources for Regional Communications: What's at Stake?

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Abstract

Contentious debate surrounds allocation of the geostationary orbit and electromagnetic spectrum, two resources used by communications satellites. An extensive economics literature alleges that the nonmarket administrative allocative procedures now in place are highly inefficient, but no research has empirically estimated the welfare loss. This paper develops a conceptual framework and a computerized model to estimate the economic value of the resources, the size and distribution of welfare costs associated with the present regulatory regime, and the potential gains from more market-like allocation.

Key Words: outer space, communications satellites, pricing natural resources

JEL Classification Nos.: H4, Q2

Table of Contents

List of Figures and Tables

ALLOCATION OF ORBIT AND SPECTRUM RESOURCES FOR REGIONAL COMMUNICATIONS: WHAT'S AT STAKE?

Molly K. Macauley[*]

A host of telecommunications services -- long-distance telephone calls, television programs, texts of newspapers and other periodicals, and an increasingly large amount of intracorporate data -- travel by way of satellite. Almost without exception, these communications satellites are situated in a particular orbit in space known as the geostationary orbit. The orbit, centered about the equator, is some 170,000 miles long--but two factors limit its use. One factor is signal interference among neighboring satellites which arises because geostationary satellites communicate at the same electromagnetic frequencies. To mitigate interference, regulations on use of the orbit require a physical distance of 800-1600 miles between satellites. The second constraint on the use of the orbit is the geographic earth coverage uniquely associated with each location along the orbit. Figure 1 indicates the countries and regions that a satellite can "see" from different locations (identified by longitudinal degree).[1] (Figures follow references at end of paper.) For example, a satellite at 250 degrees can see the Caribbean, the United States, and Canada. Such a location would be advantageous for a "regional satellite" connecting all of these countries, but not if one country wants the location solely for its own domestic use.

During the heyday of satellite communications in the late 1970s and early 1980s, communications suppliers clamored for access to the orbit, and increasing orbital congestion brought acrimonious national and international debate. Although rapid strides in fiber optic technology in the late 1980s caused demand for orbit access to level off, debate has recently resurfaced. Over 200 satellites now populate the orbit and the waiting list for access includes companies proposing new services (such as direct-to-home broadcast television and mobile communications for trucking or airline fleets) and representing newcomers, particularly developing countries, now entering the market for satellite services. Perhaps the most

[1] In this figure, as well as other figures in this paper, representation of degrees longitude uses engineering convention rather than map-making convention. The mapping convention distinguishes east and west longitude by dividing the 360 degree circle into east and west segments of 180 degrees beginning at the prime meridian in Greenwich, London. The reader can rescale the figures to be consistent with this convention by subtracting 360 from all points between 180 and 360 degrees and taking their absolute value.

dramatic recent demand is a claim by Tonga to 16 geostationary orbital locations that link the United States and Asia.[2]

Because the orbit is allocated on a first-come, first-served basis, the inefficiencies and rent-seeking typically ascribed to such nonprice administration might be expected to arise. An extensive economics literature has followed these developments, alleging the inefficiency, unfairness, or both of the regulatory process.[3] The literature frequently recommends auctions, lotteries, or other more marketlike alternatives to administrative allocation, but the literature has not yet estimated either the size of potential efficiency improvements or the distributional effects of such alternatives.

This paper describes an empirical approach to suggest the size of benefits from regulatory change, and infer the direction of gains from trade to respond to political concern about who would win and who would lose in the event of reform. Even if regulatory reform were not undertaken--indeed, it has been resisted by incumbent users of the orbit--an additional reason for improved understanding of "what's at stake" is the opportunity to make unnecessary, or at least better inform, the setting of technical operating standards for use of the orbit. Debate has typically led to increasingly stringent standards which, while intended to augment the effective supply of orbit, may also increase the investment and operating costs of satellite technology and bias technological change (Macauley, 1986, discusses these possible R&D distortions). In addition, claimstaking of orbital locations has allegedly been encouraged by two factors: the anticipation of increasingly burdensome standards and the potential for exempting compliance by incumbent users of the orbit.[4] Even if more marketlike allocation is never implemented, the approach suggested here could facilitate the present centrally-managed orbit planning process.

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[2] See Andrews (1990). See also Riccitiello and Saunders (1992) and Seitz (1994a,b,c) for discussion of debate among Pacific Rim countries over orbital access. de Selding (1992) reports new plans by the European Community to increase regulation of the orbit to reduce growing congestion and interference. In addition, the international debate has recently extended to include access to lower-earth orbits for new services such as portable telephones (see Andrews, 1992).

[3] For example, see Jackson (1978), Agnew and co-authors (1979), Levin (1981, 1988a), Webbink (1981), Wihlborg and Wijkman (1981), and Sandler and Schulze (1981). It is important to note that issues in orbit allocation mirror those in spectrum allocation, for which the U.S. Congress authorized the use of auctions in the Licensing Improvement Act of 1993. Prior to this legislation, a large economics literature, spanning some three decades, had addressed spectrum allocation; for example, see Coase (1959), DeVany and co-authors (1969), Minasian (1975), Webbink (1981, 1988), and Besen and co-authors (1984). Levin (1971) and Macauley (1986) develop quantitative estimates of spectrum shadow values. Sandler and Schulze (1981) develop Kuhn-Tucker conditions for joint allocation of spectrum and orbit. The model developed in this paper takes an approach that is similar in spirit to, but different in emphasis from, Sandler and Schulze. They do not consider the "locational amenities" of orbit or orbit/spectrum substitution possibilities.

[4] Speculative claimstaking, without making actual immediate use of the orbit, began as early as 1976 with the Bogota Declaration, in which a group of equatorial nations officially espoused property rights to the orbit as extensions of the countries' territorial airspace. Whether the social costs of claimstaking (delaying the realization of benefits from resource use) outweigh potential social benefits (when it delays irreversible investment until it is most socially profitable) is not clear. Investment is to some extent reversible in the case of the orbit and spectrum, as satellites can relocate both along the orbit and among regions of the spectrum (see Federal Communications Commission, 1983). Levin (1988a) extensively discusses claimstaking.

That process has recently begun to accept detailed engineering computer models and these could be extended to include the approach in this paper.[5]

The paper first develops and estimates an economic model of the value of locational attributes of the orbit. This model replicates the current regulatory regime in which each satellite is assigned a fixed amount of orbit and no allowance is made for the possibility of using the orbit at a given location more intensively by, e.g., having proximate satellites operate at different frequencies. The principal objective here is to estimate the savings from operating a satellite at various locations along the geostationary orbit. The savings are calculated as the difference between the cost of meeting a given demand by using a satellite at each location with the cost of meeting the same demand with the best terrestrial alternative. The result represents the maximum amount that a user would be willing to pay to operate a satellite at that location. These estimates are <u>not</u> the equilibrium price that would prevail in the market for that orbital position, but the estimates do illustrate the costs to various countries when they are not assigned their preferred (e.g., maximum cost savings) orbital location. Differences between preferred and assigned locations demonstrate one approach to estimating the costs of regulatory allocation that fails to assign a given location to a higher-valued user. This version involves a relatively straightforward calculation of relative costs.

The paper then models and estimates the effect of technological substitution possibilities that economize on the amount of orbit used at any given location. The engineering literature describes a variety of such substitution techniques. For example, satellites may be outfitted with more complex antennas to use their allocated spectrum bandwidths more intensively at a "prime" location.[6] Administrative allocation of the orbit limits the incentives to exploit these possibilities because where orbit location values are high, companies confronting such values would otherwise be induced to use orbit more intensively.

Because the locational attributes of the orbit govern demand for its use, the approach used in the paper borrows heavily from models of spatial location. In particular, models developed to study urban structure as in Mills (1972) and Mills and Hamilton (1984) are perfectly suited to characterize the orbit. The analogy with urban location is a powerful one: just as land values increase with proximity to a central business district as commuting and other transportation costs fall, orbit values might be expected to increase at locations that afford the best communications-demand related coverage. Moreover, just as an increase in land values leads to substitution towards capital and away from land (hence, skyscrapers are downtown and multi-acre, single family homes are in the suburbs), so too might an increase in orbit values lead to more capital-intensive use of the orbit at preferred locations.

To preview conclusions, results show that orbit values are highly sensitive to location and decline quickly with distance from optimal locations. When substitution is allowed between the use of orbit and spectrum (albeit using a restrictive functional form), results

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[5] See Reilly (1988) and Reilly and co-authors (1988) for engineering models of orbit allocation and discussion of their use in international negotiations.

[6] Barmat (1984) discusses these and other techniques.

indicate that the intensity of orbit use in higher-valued locations would be significantly larger than in lesser-valued locations. Taken together, these results offer a menu of policy reform, from improving the way orbit locations are allocated to permitting greater flexibility in satellite operating requirements.

The next section of the paper briefly describes the orbit and the spectrum. Section II outlines a model to estimate orbit shadow values in the case where the orbit and spectrum must be used in fixed proportions (the current regulatory regime). Section III models the effect of allowing orbit and spectrum to be used in variable proportions. The models are applied to Central and South America and the Caribbean, and the Pacific Rim, both regions that have been the subject of the most recent international debate.[7] Section IV illustrates for these regions the welfare costs of regulatory policy that fails to make use of an allocative role for location values and orbit/spectrum tradeoffs. Section V offers conclusions.

I. A NOTE ON THE RESOURCES

The geostationary orbit or "arc" is a particular location in space, about 22,300 miles above the equator. In this orbit, the velocity and travel time of satellites just offset the earth's gravity and 24-hour rotation, and satellites appear to remain as if fixed over the earth. The advantage of the geostationary orbit over other, random orbits is the ease of communications-- it allows simultaneous communications within a large region on earth, a satellite's antenna need only be pointed once at the earth, and antennas on earth need only be pointed once at the satellite. In regions where terrain or the sparse distribution of population makes alternative communications technologies more costly, satellites can assume a particularly large role in providing basic communications infrastructure. Both developed and developing countries have long been concerned with access to the geostationary orbit.

The spectrum, or airwaves, is the medium that carries communications signals. Accordingly, spectrum uses are diverse, including electronic garage door openers, terrestrial radio and television transmission, and satellites. Like the orbit, the spectrum also exhibits locational amenities; for example, satellite frequencies must be high enough to pass through the earth's atmosphere, whereas terrestrial radio frequencies can be much lower.

The locational amenities of the orbit would be the binding constraint on the resource if spectrum congestion were negligible; at this limit, satellites would only require separation of about 40 miles along the orbit to ensure that they do not bump into each other in the natural drift caused by the solar and gravitational forces of the sun and moon. In this case, other satellites could communicate at different frequencies, or be situated at non-interfering distances from other satellites communicating at the same frequency, or otherwise be "coordinated" in the timing of their communications.[8] Regulatory-specified spectrum assignments limit these

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[7] Macauley (1987) applies a limited, earlier version of the model to North America.

[8] "Frequency coordination" is practiced voluntarily and extensively among other users of spectrum--a manifestation of Coase's "theorem"; there is also evidence that satellite operators coordinate their transmissions to avoid interference (see Federal Communications Commission Report and Order, 1983, paragraph 43).

opportunities, however, and the specter of signal interference has led regulators to mandate orbital separations of from 800 to 1600 or more miles.[9]

II. ESTIMATES OF SITE VALUES UNDER THE EXISTING REGULATORY REGIME: THE FIXED PROPORTIONS CASE

Given that locational differences appear to be the binding constraint on orbital use, this section outlines an approach to estimating these locational amenities. In this model satellite technology is characterized as fixed proportions in its use of orbit and spectrum in order to suggest the size of inefficiencies associated with the current regulatory regime if location assignments fail to reflect their highest valued uses. The pattern of orbit location values estimated in this section also plays a key role in the more general model of section III (where some substitution between of orbit and spectrum *is* permitted).

A. The Model

The market for satellite-related services ultimately determines the derived demand for a location in the orbit. In the model in this section, the quantity demanded of telecommunications is taken as exogenous and the decision variable is simply the choice of the lowest cost technology -- satellite-based or terrestrial-based -- to meet demand. The model calculates the potential cost savings enabled by using satellite rather than terrestrial technology, when the satellite is at a given orbital location and has a fixed amount of orbit for operations. Satellites may present a cost advantage because they can "see" (or be seen by) and hence interconnect all geographic areas within its field of view (FOV), whereas terrestrial technologies such as fiber optics or terrestrial microwaves require an extensive network to interconnect the same set of areas.

The model estimates these cost savings given one location of a satellite, then another, and so on for each possible location along the orbit. These savings represent the maximum amount that a cost-minimizing telecommunications firm would pay for access to a specific location. The amount is an upper bound because willingness to pay is also likely to depend on the savings afforded by other locations.

Equations (1) through (5) below are the building blocks of the simulation model. For an output of communications services, Q, production of communications using satellite (subscript s) or terrestrial technologies (subscript $i = 1$ to m) is represented by:

$$Q_S = Q(A, S, H_s) \text{ and} \tag{1}$$

$$Q_i = Q(H_i), \tag{2}$$

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[9] The industry has in fact implemented some engineering designs that limit spurious emissions or protect signals against second party interference. These steps lead to some possibilities for reduced orbital spacing, but even larger possibilities from the engineering literature on orbit and spectrum substitution underlie the technology in Section III. In addition, interference is reduced if colocated (that is, neighboring) satellites use sufficiently sophisticated antennas aimed in different directions (say, north to the U.S. and south to Chile).

where satellite technology uses orbit (A), spectrum (S), and hardware (H_s) and the alternative uses hardware (H_i).[10] For n countries that desire to be interconnected, each of two countries in any pair of countries is referenced by j and k. Expenditure for intercountry communications are minimized if the countries jointly choose the least costly technology C_{ijk}:

$$C_{ijk} = C_i(Q_{jk}, Z_{jk}, \mathsf{d}_i(\overline{Q}_i)) \quad \text{and} \tag{3}$$

$$C_{sjk} = C_s(Q_{jk}, \mathsf{d}_s(\overline{Q}_s); L_1, \ldots, L_{\mathsf{t}}) \text{ for } (j,k) \in FOV \tag{4}$$

where $\mathsf{d}(\overline{Q}) = \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} Q_{jk}, \quad 0 < \mathsf{d} \leq 1.$

Equation (3) takes explicit account of the distance, Z, between countries j and k. Distance is a factor in (3) because terrestrial technologies require signal repeaters. The expression $\overline{Q}$ is the total quantity of communications demand for the set of countries. In both (3) and (4), the term $\mathsf{d}(\overline{Q})$ reflects indivisibilities in the various technologies when they operate as a system-- in other words, the installed capacity of the system as a whole will typically exceed demand on a single country-pair route.[11] In Equation (4), L refers to an exogenously given orbital location, indexed by 1 through t, and also requires any country pairs that use a satellite to be in the satellite's field of view.

An additional constraint that represents a prominent aspect of communications production measures the "busy hour" traffic expected between the countries. In (5), $Q_{jk}{}^{D}$ measures this traffic and ensures that facilities have sufficient capacity to handle peak volume with a suitable grade of service (that is, a low probability of receiving a busy signal).

$$Q_{jk}{}^{D} <= \overline{Q}_{jk} \tag{5}$$

This grade of service value is taken from engineering literature and is discussed below in describing the data on telecommunications demand.

Using these equations, the model calculates for each country pair the least cost technology, satellite or terrestrial, given each location of a satellite. The choice depends on the traffic and distance between the countries--satellites tend to be less expensive for low capacity, long distance routes--and whether the satellite is in view of the countries (if it is not in view of both countries, terrestrial technology is used). The total cost of regional

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[10] H_s includes launch of the satellite; H_i includes coastal landing rights, in the case of undersea cable, or overland rights of way in the case of terrestrial fiber.

[11] Satellite producers are developing the next generation of satellites in a continuum of sizes so that satellite sizes could be matched to geographic coverage, thus improving the efficiency of orbit use.

communications for each satellite location is then calculated by summing over all country pairs within a geographic region--e.g., South America or the Pacific Rim.[12]

By way of example, suppose a satellite is located at L_1 and is within view of at least some countries in one of the regions. When each country pair in the region minimizes C_{jk} then the minimum total cost, given L_1, is represented by (6):

$$\sum_{j=1}^{n-1} \sum_{k=j+1}^{n} C_{jk}(Q; \mathrm{d}, z, L_1) = min\ TC(L_1) \tag{6}$$

If the satellite were located such that none of the countries in the region were within view, say, at L_x, (6) could be recalculated for $TC(L_x)$. Denoting the cost savings associated with location L_1 as $R(L_1)$ gives $R(L_1) = TC(L_1) - TC(L_x)$.[13] The set of R's, each indexed by location L and calculated by subtracting $TC(L_x)$, represents a relative orbital site value. Differences among the R's reflect the additional costs incurred by the country pairs whose cost-minimization decisions are constrained by satellite location. As noted earlier, these values are an upper bound on maximum willingness to pay because a firm would be willing to pay as much as $R(L_1)$ only if the next best available site were L_x.

B. The Data

This section briefly describes the cost and demand data. Additional details about data sources and methodology are in the appendix.

Technologies

In addition to satellite technology, the other technologies that are choices for the geographic regions studied here are land and undersea fiber optics[14] which operate by the transmission of light through glass fibers and are not competitors with satellites for spectrum allocation. The cost data include engineering estimates of operating and investment costs of both the satellite and ground segments, and of fiber installations including long-haul landing (for undersea cable) and connections to major cities. All three technologies are characterized by a high ratio of fixed capital to operating costs--annual operating costs are approximately four percent of investment costs for satellite systems and seven percent for the alternatives. Costs are measured at minimum long-run average cost, and all investment costs are

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[12] The regional aggregation is taken because it seems to be the focus of international debate; as noted earlier, the model can operate at any level of aggregation.

[13] $R(L_1)$ is greater than or equal to zero; it cannot be less than zero because an option at L_1 is not to use satellite technology, in which case $TC(L_x) = TC(L_1)$.

[14] Other alternatives--terrestrial microwave facilities or coaxial copper cable--are reported by most observers to be too expensive, given the types of terrain--mountainous, jungle, and ocean--in the regions investigated in this paper. See discussion in Lee (1987) and Miglio (undated; also 1988) (references cited in data appendix).

annualized assuming a five percent interest rate, satellite lifetimes of ten years, and fiber system lifetimes of 25 years.[15]

<u>Demand</u>

For each country pair, demand is estimated at peak period traffic on a weekday. The demand data are based on country populations weighted by the estimated percentages of the fraction of the population engaged in international communications during peak hours based on international calling statistics.[16] These data are probably satisfactory relative orders-of-magnitude proxies for other types of telecommunications services such as television broadcast or text transmission that might be demanded in the regions.[17]

C. Estimates of Orbit Site Value

Using these cost and demand data, the model calculates the annualized values of orbit locations (R). The curves labeled "Fixed Proportions" in Figures 2 and 3 display these values. (Figures follow references at end of paper.) Figure 2 represents North America, Central America, South America, and the Caribbean nations (referred to as "SoAmer"), and Figure 3 represents Pacific Rim countries ("PacRim").[18] Estimates range from $0 to $30 million for SoAmer and $0 to $27 million for PacRim.

In the case of SoAmer, site values reach a maximum when the number of countries within view of the satellite is also a maximum. Tracing the pattern of site values, site values increase as the number of countries in the field of view increases. From 0 to 180 degrees, most of the countries are outside of the field of view. At 182, Mexico comes within view, and at 204, about half of the U.S. is in view. The large jump at 212 reflects the interconnection with a portion of Canada. Chile, Bolivia, Venezuela, Bermuda, Guadeloupe, Trinidad, Barbados, Argentina, Paraguay, Uruguay, and Brazil next enter (roughly in that order) such

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[15] These lifetimes are standard in the engineering literature; see Martin (1978) and Dawidziuk and Preston (1970) (cited in data appendix).

[16] Specifically, following engineering convention, the volume of peak-hour traffic is the volume of ten-minute calls placed during busy hours. In addition, and also using engineering data, capacity is sized to minimize the probability of obtaining a busy signal subject to estimates of consumer willingness to tolerate such a signal. The call data reflect existing pricing schemes. The implications of demand elasticities are considered in Section III.

[17] Telephony, television, and text have traditionally represented about 90 percent of commercial satellite communications traffic until recently; now, about one-third is direct-to-home television and mobile communications (see Smith, 1996). See also Acton and Vogelsang (1990) for their observations that calling is correlated with trade volumes and employment among geographic regions.

[18] Countries in the first region are Argentina, the Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Columbia, Costa Rica, Ecuador, El Salvador, French Polynesia, Guadaloupe, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Paraguay, Trinidad, Mexico, Panama, Peru, Uruguay, and Venezuela. The second region consists of Australia, China, Hong Kong, Indonesia, Japan, South Korea, Malaysia, New Zealand, the Philippines, Papua New Guinea, Singapore, and Thailand. Canada and the United States are also included in both regions (with international calls assumed to originate and end in Montreal, Los Angeles, and New York City in the first region, and Ottawa and Los Angeles in the second region).

that at 236 to 288, all 29 countries in the SoAmer data set are in the field of view, and site values are maximized. The large decline at 320 occurs as Los Angeles is excluded, and at 342, Mexico is outside. The contribution of satellite links to Canada and the United States is underscored by site values from 342 to 360; while Canada and the U.S. are not in view at those locations, 26 out of 29 countries are in view.

The values for the PacRim region exhibit a slightly different relationship between site values and the field of view. The relationship is not monotonic with respect to the number of countries in view of the satellite but also depends on the amount of communications among them. For this reason it is notable that in all figures pertaining to the PacRim, site values remain high when Canada and the U.S. are in view even though large numbers of PacRim countries are outside the field of view. From about 30 to 176 degrees, 12 out of 14 of the PacRim countries are viewable (but Los Angeles and Vancouver are not viewable). At 176 degrees, Los Angeles enters the field of view, and from 176 to 190, the number of countries although not the site value is maximized. From 190 to 216, several countries exit the field of view, beginning with Singapore and ending with Seoul, and site values decline. The large jump at 220 occurs when western Canada comes into view, and from 220 to 226, values are maximized. In this region, Australia, western Canada, Japan, New Zealand, Papua New Guinea, and the west coast of the U.S. are in the viewing range. Values decline again with the loss of Australia and Papua New Guinea at 226. They sharply decrease at 320, where Los Angeles leaves the field of view.

The magnitude of site values reflects the geographic distribution of population and land mass, distance and terrain (ocean or land); and income, trade, and other factors that determine interregional telecommunications patterns. The small values (around $1 million) for the orbit locations where the largest number of PacRim countries is within view largely reflect the relative efficiency of ocean fiber (it is a lower-cost technology when distances between countries are small and communications traffic is high).[19]

As a general perspective on the reasonableness of the values, they are overestimated if the estimated engineering costs of the satellites and ground stations are too small or if opportunities for scale economies in use of all of the technologies are underexploited in the simulation.[20] Values are underestimated to the extent that domestic communications and international traffic for services other than telephone service are omitted. Based on fees for existing routes that appear to be the most competitive (that is, where multiple satellite- and

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[19] This observation is consistent with the treatment in the engineering telecommunications literature of two subregions, the Greater Pacific and the Western Pacific (see Miglio, undated). The subregions are identified in Table 4.

[20] The latter occurs if demand were measured at a too disaggregated level. For example, demand is presently measured as the sum of traffic between Venezuela and Canada, and between Brazil and Canada. Greater scale economies may be realizable if demand were estimated as an aggregation of calls from Venezuela and Brazil to Canada. However, doing so would require some additional costs for added telecommunications facilities to bundle the traffic--more fiber, or use of terrestrial microwave, or additional satellite capacity.

terrestrial-based firms serve the market), published fees per call closely approximate the price per call implied by the maximum estimated site values.[21]

III. THE MODEL WITH SUBSTITUTION POSSIBILITIES

In the model above, satellites are uniformly spaced along the orbit to comply with existing regulation. The engineering literature and many experts suggest that the spacing is larger than would be necessary if satellite technology were allowed to combine use of orbit and spectrum more flexibly. The model in this section permits substitution between these inputs, as might be triggered by location-induced price changes in the value of the orbit. As noted in the introduction, the approach is based on the model of spatial location in Mills and Hamilton (1984).

A. The Model

Demand and supply

Components of this more general model include supply (7) and demand equations (8) for communications:

$$X_s(u) = D \, A(u)^a \, S(u)^{1-a} \tag{7}$$

$$X_d(u) = b y^{q_1} p(u)^{q_2} \tag{8}$$

In (7), D is a scale parameter; A and S are, as in equation (1), quantities of orbit and spectrum; and α is the distribution parameter, $0 < a < 1$. In the demand equation (8), b is a scale parameter; y and p are income and price; and q_1 and q_2 are income and price elasticities, respectively. The use of orbit and spectrum and the price of communications services are functions of satellite location, here denoted as location relative to prime locations (where values are at a maximum) and measured as "u."

The Cobb-Douglas form assumed for the production function is very restrictive. Data are unavailable to estimate all of the parameters involved in a more flexible functional form, but some anecdotal engineering about use of orbit and spectrum is available to shed light on the Cobb-Douglas restrictions. These restrictions require that the ratio of input use be proportional to the ratio of factor prices (and the implied substitution elasticity is one). Although, as emphasized earlier, present satellite operating regulations restrict flexibility in combining orbit and spectrum, some satellites employ spectrum so as to use their orbit allocation somewhat more intensively. Based on published operating parameters, these satellites use a unit of orbit in a prime location some 7 to 10 times more intensively than in

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[21] See fees reported in "Satellite Operators Activate the Money Star," *The Economist*, 3 May 1997, pp. 56-57.

nonprime locations.[22] To compare this with the factor price ratio, orbit values estimated in the preceding section show values in prime locations some 10 times larger than in nonprime locations (compare $30 million to $3 million in Figure 2, or $27 to $2.5 million in Figure 3).[23] Factor proportions of 7:1 imply that the elasticity of substitution is less than one. If factor proportions are 10:1, the implied elasticity of substitution is one.

Locational equilibrium

The final equation required in models of spatial location is an expression to preserve locational equilibrium. Along the orbit, such an equilibrium would be preserved by location-induced compensating changes in prices that make suppliers of communications indifferent among locations. Equation (9) models the equilibrium-preserving price change (hence the derivative p'):

$$p'(u) X_d(u) = -t(u) \, , \tag{9}$$

The expression $t(u)$ represents the extra costs to interconnect cities outside the view of the satellite; in other words, $t(u)$ are the extra costs incurred to get to the edge of the field of view of the satellite. Satellite connection costs are thus low when the satellite is in a prime location and high in less desirable locations.

The values of $t(u)$ can be derived from the results in the preceding section. For example, from Figure 2, providing telecommunications using a satellite located at 330 degrees incurs extra interconnection costs of about $23 million compared with using a satellite at 270 degrees in Figure 2 ($30 million - $7 million); using a satellite at 270 degrees incurs no extra costs for this region. To parameterize $t(u)$, the values in Figures 2 and 3 were fit using the computer program *Mathematica*, which estimated a polynomial of the form in (10):

$$t(u) = \gamma \, \frac{e^{((u - \bar{u})/\sigma)}}{1 + e^{((u - \bar{u})/\sigma)}} \tag{10}$$

In (10), $u - \bar{u}$ measures distance (in longitudinal degrees) at u from the prime orbit location, $\bar{u}$; σ is a parameter estimated in curve-fitting, and γ is a scale factor. The fit is intentionally made to be the lower envelope of the site values estimated earlier, in that these represent the

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[22] They employ techniques to "re-use" spectrum as described in Martin (1978) and Dickson (1996); the tables in Dickson and in *Space News*, June 16-22, 1997, p. 8 ("Geosynchronous Communications Satellites Covering Africa, Europe and the Middle East") give the spectrum re-use information for satellites at various orbital locations.

[23] In the factor price ratio, the price of spectrum is assumed invariant with respect to location.

upper bound on maximum willingness to pay for any given location.[24] The function declines with distance from $\overline{u}$, and the rate of decline reflects the s-shape described earlier.

<u>Deriving site values, R.</u>

The site value of an orbital location, *R*, is derived using equations (7) through (10). The steps taken are shown in the appendix; they give

$$R(u) = [\overline{R}^{\,b} + E\mathsf{sb}][\ln(1 + e^{((u^*-u)/\mathsf{s})}) - \ln(1 + e^{((u^*-u)/\mathsf{s})})]^{1/\mathsf{b}} \tag{11}$$

for $\mathsf{b} \neq 0$ [25] where $R(u^*) = \overline{R}$ is the initial condition and u^* is the orbital location where site values approach zero.

B. Estimates of Orbit Site Values

Equation (11) expresses the differential equation (9) in terms of *R(u)*. The curves labeled "Variable Proportions" in Figures 2, 4, and 5 show the results of applying (11). (Figures 4 and 5 are enlargements of hard-to-see portions of Figure 3, and divide PacRim into the Greater Pacific and Western Pacific regions.) The data and parameter assumptions are listed in Table 1 and σ is estimated in the curve-fitting procedure. Sources of income and price data are given in the appendix.[26]

Comparing "Fixed Proportions" and "Variable Proportions" in the figures suggests that higher site values in "prime" locations would elicit substitution away from orbit to the extent permitted by the production technology and demand parameters. Site values at prime locations are about 30 percent lower for the SoAmer and the Greater Pacific regions, for instance. In addition, substitution appears to decrease in more remote locations as locational values shift relative factor prices. The "Variable Proportions" values are much closer to "Fixed Proportions" values at these more remote sites.[27]

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[24] The smoothing of fitted values lends not only analytical tractability, but also may better approximate values if continuously variable units of orbit rather than fixed quantities could be used.

[25] The case for $\mathsf{b} = 0$ is $R(u) = e^{E/\mathsf{s}}(1 + e^{((u^*-u)/\mathsf{s})})^{-1}$ but is not considered here, given that parameter estimates taken from the literature suggest nonzero b.

[26] There exists no consensus on communications demand elasticities, and empirical estimates vary widely. Rea and Lage (1978) find an income elasticity of 1 and a price elasticity of -.7. Among the most recent estimates for calls originating or terminating in the United States in particular, Acton and Vogelsang (1990) find that the price elasticity for telephone calls originating in the United States is -1 during 1983-1986 and insignificantly different from zero during 1979-1982; for calls terminating in the U.S., price elasticity is more inelastic (around -.5) during both periods. See also Taylor (1980) for discussion and summary of demand elasticities for international telephone calls.

[27] The number of calculated data points is much larger along the curves labeled "Variable Proportions" because the model has essentially been transformed from estimating discretely to estimating continuously along the orbit, since firms can more flexibly use quantities of orbit.

Table 1. Parameter Values (dollar values are 1990 dollars)

Income elasticity (q_1)	1	
Price elasticity (q_2)	-1	
Factor shares-Orbit (a)	.5	
Factor shares-Spectrum (1-a)	.5	
Spectrum shadow values (s) (per 40 MHz at 4-15 GHz)	$.9-2.3 million	
Mean per capita annual income (w)	$3,400 (SoAmer)	$5,700 (PacRim)
Mean price (10 minute call) (p)	$11 (SoAmer)	$17 (PacRim)

An implication of these results is that orbit/spectrum regulatory schemes permitting exploitation of site values and flexible input proportions might yield a markedly different pattern of intensity of resource use. The spectrum/orbit ratio at each location is:

$$\frac{S(u)}{A(u)} = \frac{1-a}{a}\frac{R(u)}{S} \tag{12}$$

Using results represented by Figure 2 and parameters from Table 1, use of an orbital location in the highest-valued region for SoAmer would have a spectrum/orbit ratio about 50 percent larger than in the next-best location (moving east).

C. Sensitivity of Results to Parameter Values

Table 2 illustrates results under different assumptions about the values of various parameters. The effects of larger or smaller different demand elasticities appear to make only slight differences in the estimated prime site value. Changes in factor shares, however, have larger effects, although the effects are still small.

Table 2. Sensitivity Results

	Parameter Values				Change in Estimted Prime Site Value		
	θ_1	θ_2	α		SoAmer	Western PacRim	Greater PacRim
(a)	--	--	.7	increases factor share of orbit	+2%	+1%	+6%
(b)	--	--	.3	decreases factor share of orbit	-2%	-1%	0%
(c)	1.5	-1.5	--	increases income and price elasticities	-2%	0%	0%
(d)	.2	-.2	--	reduces income and price elasticities	+.5%	+.3%	+.2%

IV. WELFARE COST

The models above illustrate several measures of the social cost of orbit and spectrum regulation. For example, what is the cost if a region does not receive its most-preferred, but its "next-best" preferred location? Or, what is the cost if a region receives its "least-preferred" orbital location?

Tables 3 and 4 illustrate estimates of these costs. The "worst case" costs associated with fixed proportions are obtained by assuming that regions are assigned their least-preferred orbital locations. The smallest welfare loss is obtained by assuming the assignment of second-most preferred locations. From Figure 2, the worst case amounts to about $30 million for SoAmer. In the second-most preferred case, the loss is about $1 million if the locational assignment is to the west (to the left in Figure 2) and about $23 million if to the east. From Figures 4 and 5, for the Western Pacific and Greater Pacific regions, the worst cases are $27.4 million and $2 million, respectively. For both of the Pacific regions, the next-best preferred locations moving west involve loss of connections to the U.S. and Canada and under the demand conditions assumed here, the social cost is the same as the worst cases. Moving east, the penalty is much smaller.

Table 3. Estimates of Annual Welfare Cost Based on Satellite Location: Central and South America and the Caribbean (millions of 1990 dollars)

Fixed Proportions		
Least preferred		$30.1
Next-best preferred:	west	1.0
	east	23.0
Variable Proportions		
Least preferred		$21.0
Next-best preferred:	west	.5
	east	4.0

Table 4. Estimates of Annual Welfare Cost Based on Satellite Location: Pacific Rim[a]   (millions of 1990 dollars)

Fixed Proportions			
Least preferred		$27.4	$2.2
Next-best preferred:	west	24.0	2.2
	East	.15	.1
Variable Proportions			
Least preferred		$27.0	$1.6
Next-best preferred	west	27.0	1.6
	East	.01	.1

Note:

[a] The Greater Pacific subregion includes Australia, New Zealand, Papua New Guinea, Japan, and the west coasts of Canada and the United States. The Western Pacific subregion includes all of these countries and Korea, the Philippines, China, Hong Kong, Indonesia, Malaysia, Singapore and Thailand.

        Of course, the costs are less when a more flexible orbit/spectrum technology is
assumed. In this case, for SoAmer the cost of a least-preferred location assignment is about
$21 million and of a second-best preferred location, $.5 to $4 million (depending on whether
the location is west or east). Using Figures 4 and 5, the worst case is $27 million for the
Western Pacific and about $1.6 million for the Greater Pacific. Moving east, the costs are
much smaller.

        An additional question naturally arises when opportunities to economize on the use of
the orbit are considered, namely might improved opportunities for factor substitution also
have potential beneficial effects in "freeing up" orbital locations? Economizing on orbit in
prime locations can increase the availability of such locations to users able to afford prime
access; it may also free up access at the margin to less well-off users or new entrants. There
are some 77 longitudinal degrees of orbit that afford coverage of the 48 contiguous United
States (recall Figure 1); almost all of these locations are currently assigned. The model in this
section can be completed by noting the total amount of orbit available to each of the two
regions as bounded by the orbit location where site values fall to zero:

$$\int_{u_1}^{u_2} R(u)\,du = \textf{}u \,,$$

where u_1 and u_2 represent zero-valued "edges" and ϕ is the total amount of orbit in this
relevant range. Reducing intersatellite spacing from current requirements (between 2 and 3
degrees, depending on certain operating characteristics) to those implied by the results here
(about 1 to 1.5 degrees) could increase capacity by 60 to 140 percent in each of the regions.

        Would potential entrants gain in this case? Some anecdotal evidence from current
trade literature illustrates who may gain. The Andean pact nations (Bolivia, Colombia,
Ecuador, Peru, and Venezuela) have advanced plans for a $1 billion, two-satellite system for
the region, using orbital locations of prime value to most countries in the western hemisphere.
The Pact also acknowledges that its intent is in part to ensure future orbital access, as the
system will operate with significant spare capacity at the present time. The total annualized
costs are approximately $130 million, and as the satellites are intended to operate at larger
spacing, could require the equivalent of four locations. Orbit values estimated for the United
States suggest annual site values of about $30 to $90 million.[28] Thus, there are potential net
social gains from mechanisms that would facilitate such tradeoffs, as four locations might
total $120 to $360 million (as valued by the U.S.). The trade could take place as an exchange
of lower- for higher-valued sites, greater intensity in the use of a site (for example, more

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[28] See Macauley (1987) for the larger estimate. The lower value is based on recent satellite sales data. The
variation reflects in part yet another locational amenity not captured above, that related to agglomeration benefits
of sharing a single satellite--cable television distributors, for instance, prefer only to aim an antenna at one
satellite loaded with popular programs, rather than several satellites each with just a few programs even if the
latter satellites are all well-located.

intensive spectrum use at high-valued locations), or some combination of the locational and factor-intensity possibilities.

V. CONCLUSIONS

These results suggest potential gains from regulatory reform to exploit locational advantages and substitution opportunities in use of the geostationary orbit and electromagnetic spectrum. Although the estimated magnitude of potential savings is small compared with the size of the worldwide telecommunications industry, the possible savings are large compared with the telecommunications sector in a developing country or with the annual budget for communications satellite R&D in the U.S. (about $2 million). Thus, the cost savings may well justify attention to regulatory reform.

Clearly a major impediment to realizing such gains, however, is the lack of well-defined property rights to the orbit.[29] Moreover, as Hazlett emphasizes in the context of the spectrum,[30] these rights should probably be specified as a right to the resource, not a license for operating a communications service. The difference is that the opportunity conveyed by the property right to configure a satellite system makes best use of both a location along the orbit and the quantity of orbit used there, and is a way to ensure that the resource is most effectively used.

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[29] See Levin (1988b) for instances of cash exchanges in extra-market transactions. Like most mechanisms operating to circumvent regulatory constraints, a key concern is the extra transactions cost associated with circumvention. Would a legitimate market reduce negotiations costs?

[30] See prepared statement of Thomas Hazlett (1995), in U.S. Senate, Committee on Commerce, Science, and Transportation, *Hearing on Spectrum Auctions*, 12 September, pp. 67-73.

APPENDIX: DERIVATION OF SITE VALUE EQUATION (10)

The usual factor price expressions for $A(u)$ and $S(u)$ substituted into the supply equation (7) give

$$p(u) = [D a^a (1-a)^{1-a}]^{-1} s^{1-a} R(u)^a \tag{i}$$

where lower case s is the shadow price of spectrum. From (i), the prices of communications services are proportional to site value $R(u)$ raised to a power between 0 and 1; whenever orbit site values are high, communications prices would also be high, although they rise less rapidly because of input substitution. For example, if a is .1, a 10 percent rise in orbit "rent" would lead to a 1 percent rise in communications prices.[31]

Next, using the derivative of (i) with respect to u and substituting for X_d from (8) and for $p'(u)$ from (9) gives

$$E^{-1} R(u)^{b-1} R'(u) + t(u) = 0, \tag{ii}$$

where E and β stand for collections of constants:

$$E^{-1} = aby^{q_1} [D a^a (1-a)^{1-a}]^{-(1+q_2)} s^{(1-a)(1+q_2)},$$

and

$$b = a(1+q_2).$$

Using $R(u^*) = \overline{R}$ as the initial condition, where u^* is the orbital location where site values approach zero, (ii) can be solved for the site value given in the text as equation (11).

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[31] Note here that the price of orbit but not of spectrum or hardware depends on location. From the theory of rationing (see Deaton and Muelbauer, 1980), a change in the price of a rationed input does not affect compensated demand for the unrationed input, such that Hicksian and Marshallian demands coincide when the latter are evaluated at the cost-minimizing point. Accordingly, price changes associated with changes in location have an expenditure effect only; in the model, price decreases reduce the compensated (that is, the Q-constrained) demand for the unrationed (hardware) input to the extent inputs are substitutable. Technically speaking, the estimates of welfare change arising from this procedure represent producers' compensating variation--that is, the changes are measured from the production side not the demand side, thus holding demand curves constant.

DATA APPENDIX

Data Sources and Methodology

Telephone Statistics: The number and geographic distribution of calls are from *International Telecommunications Yearbook* (United Nations, 1992) and *The World's Telephones as of January 1, 1992* (AT&T). For Haiti and Guatemala, data are not reported but are assumed equal to statistics for neighboring countries with similarly sized populations. For Belize, Bermuda, Cuba, Nicaragua and Jamaica, data are interpolated from years reported to obtain estimates for 1992. For countries where data are reported in minutes of calls, data are divided by 10 to obtain the number of 10 minute calls per year. Data used in simulation model in text are estimated number of calls per 10 minute interval during a weekday. Price data are from Federal Communications Commission (1991), Table 34, pp. 120 - 122 and AT&T International Telecommunications Guide (July, 1990). Price is measured by the sum of the initial period rate plus the additional per minute rate (for nine additional minutes) at standard rates. A regional average is calculated as the unweighted mean of rates for countries in the region (matched to the "schedule numbers" used to identify country rates).

Latitude and Longitude coordinates for major cities: *Britannica Atlas*

Undersea Fiber Optic Costs and Lifetime: Lee (1987); Miglio (undated and 1988); Federal Communications Commission (1984); Dawidziuk and Preston (1970).

Satellite Costs and Lifetime: Lee (1987); conversations with Dave Lee, Director, Ground Segment Engineering and Development, COMSAT (March 1983); "Satellite Costs" (NASA, undated mimeo); Martin (1978).

Land Fiber Costs: *Public Utilities Fortnightly* (1984), Bell (1984), and conversations with and information provided by Christopher Pleastsikas (April 1985).

Spectrum Shadow Values: See Macauley (1986a,b).

Income and Population Statistics: *World Bank Development Report (1990)* and *World Bank Atlas* (1990).

Orbit/Spectrum Production Technology: Industry data submitted as background reports to Federal Communications Commission (1985). The reports offer summary data on modulation, polarization schemes, antenna patterns, and other techniques that substitute between orbit and spectrum while maintaining a constant quality/quantity signal.

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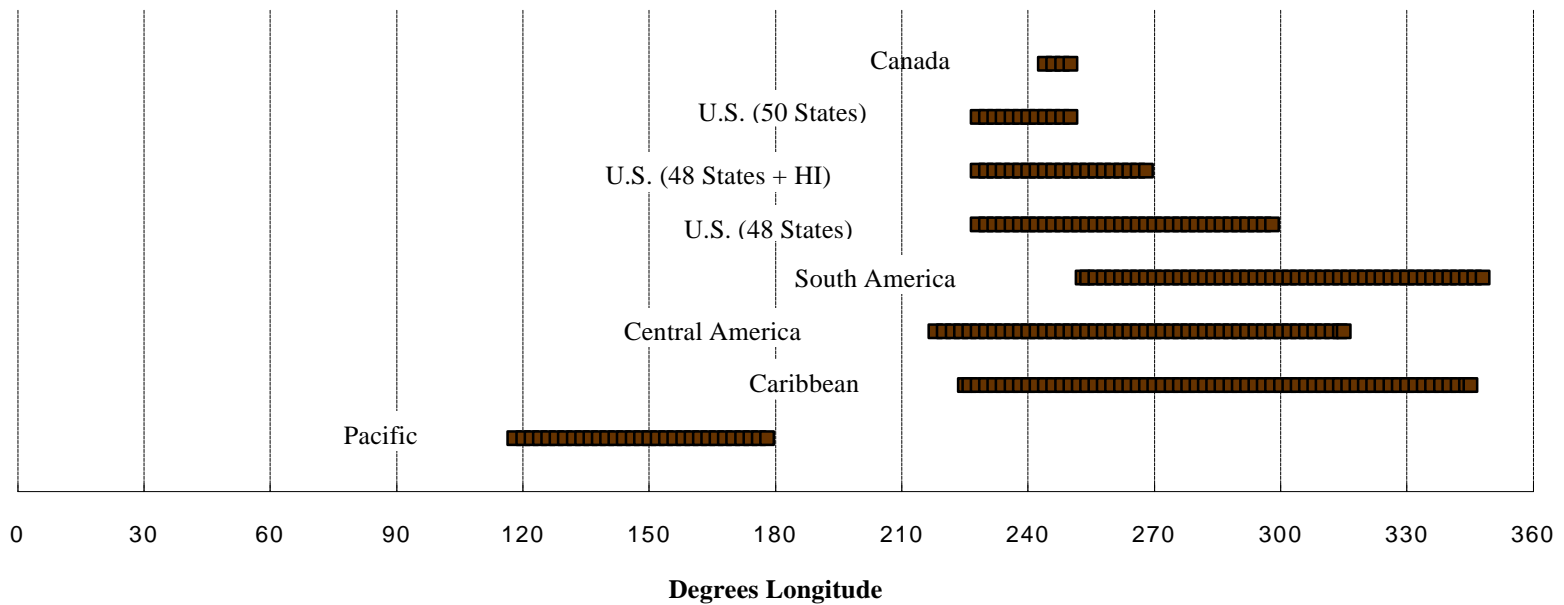
Figure 1. Geography of Satellite Footprints showing from which orbital locations, denoted by longitudinal degrees, the country or region indicated is within the field of view of the satellite
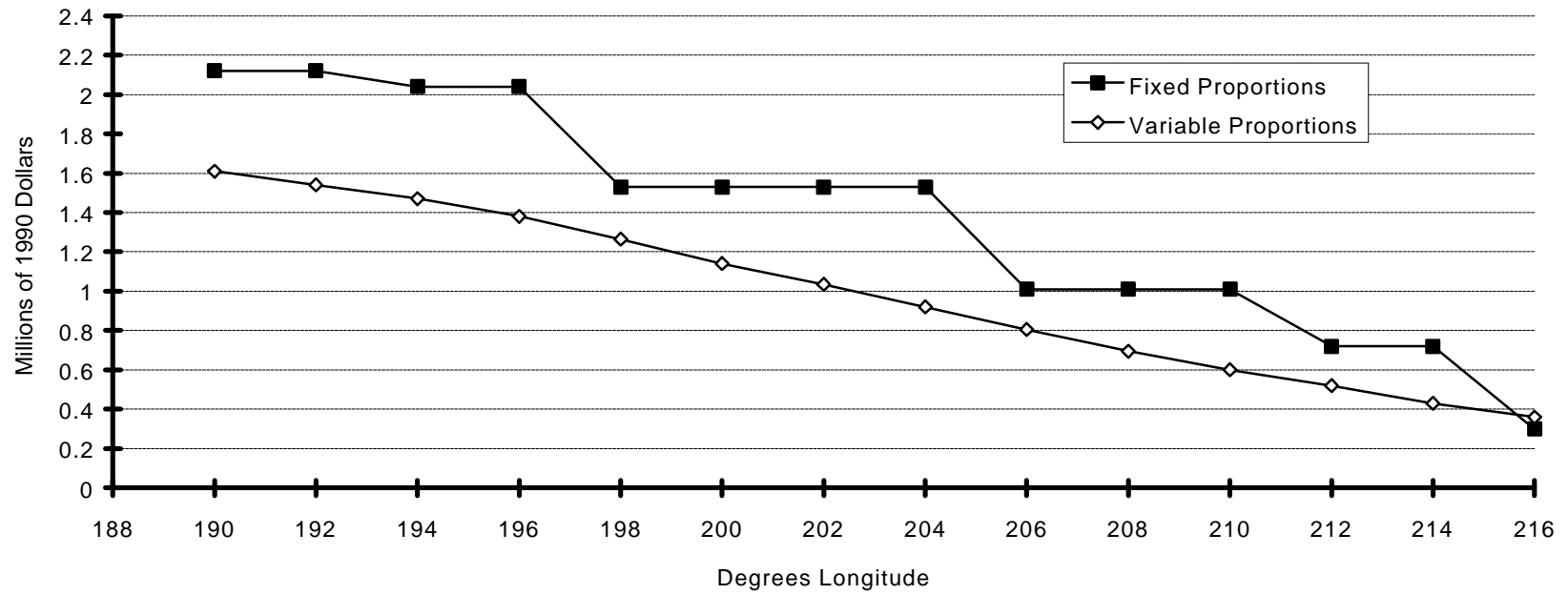
Source: Reinhart, 1974

23
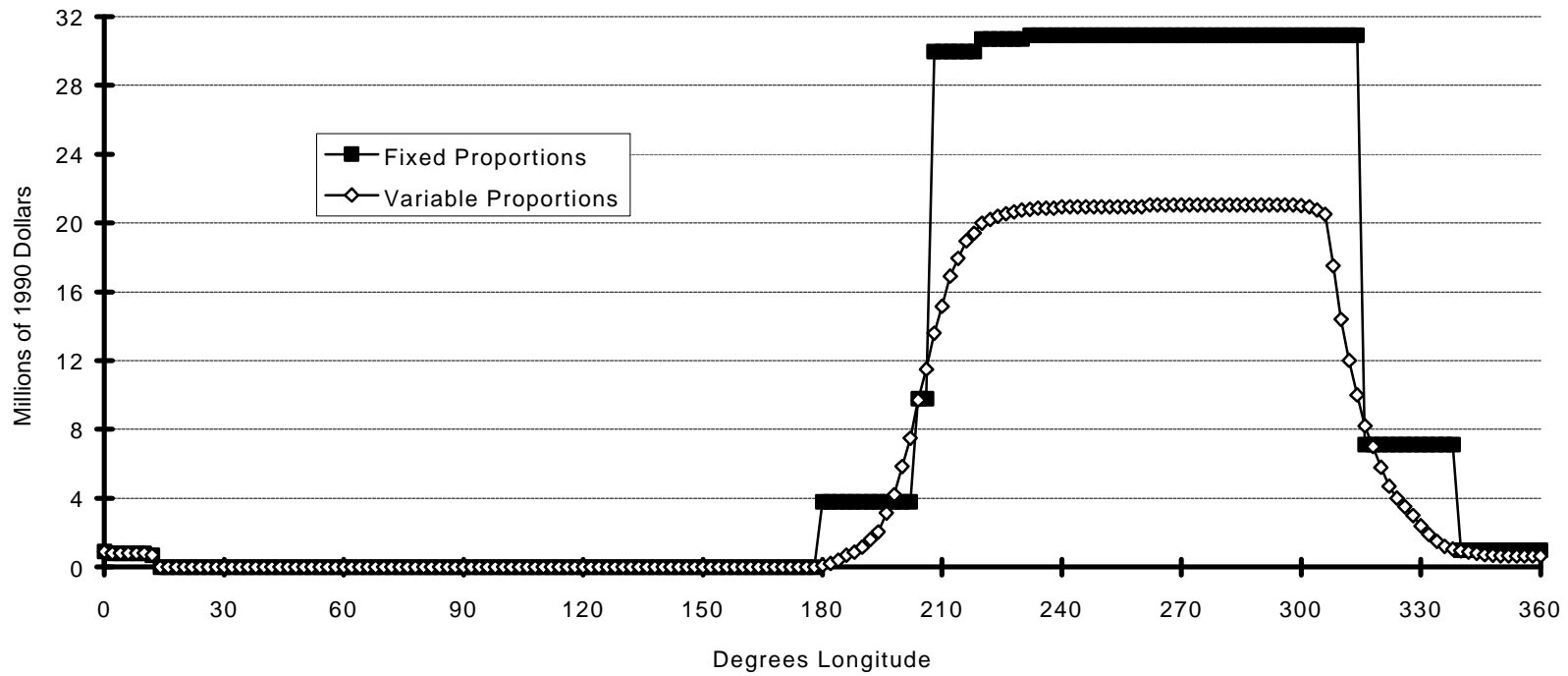
Figure 2. The Geostationary Orbit: The Estimated Cost Savings by Satellite Location for Countries in Central and South America and the Caribbean
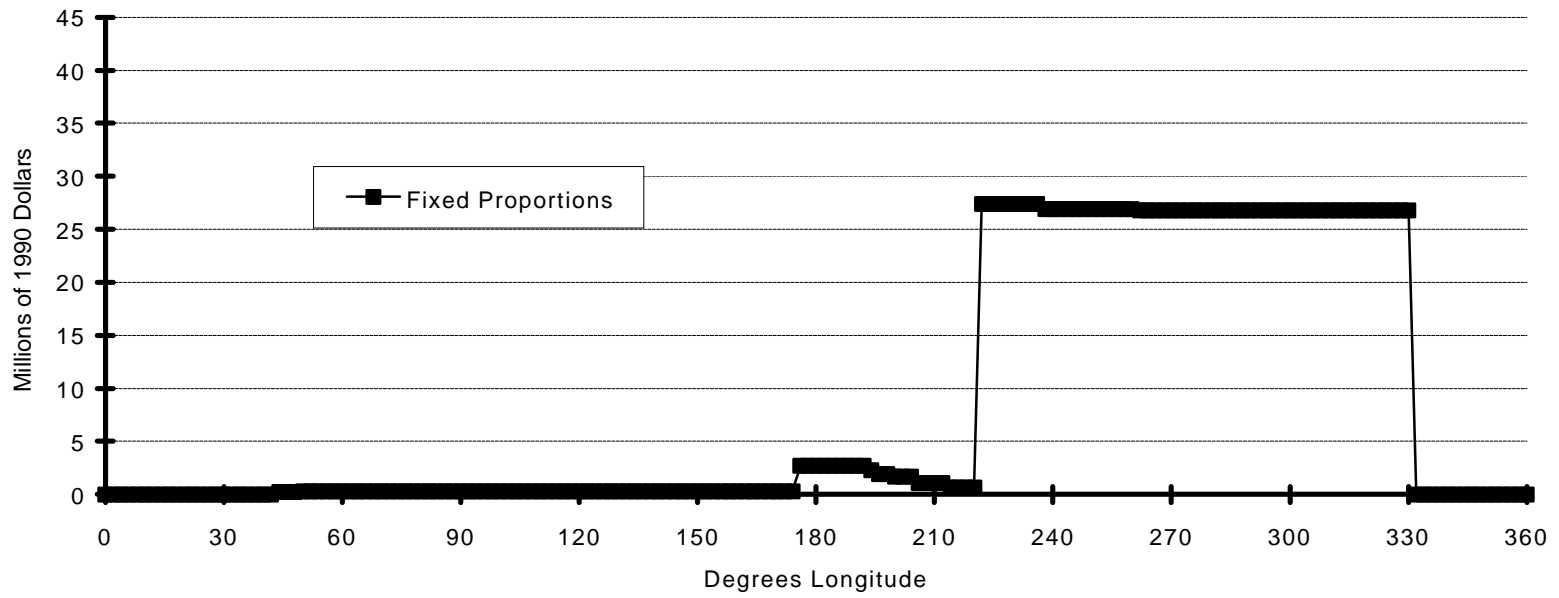
Figure 3. The Geostationary Orbit: The Estimated Cost Savings by Satellite Location for Countries in the Pacific Rim

Figure 4. The Geostationary Orbit: The Estimated Cost Savings by Satellite Location for Countries in the Greater Pacific Rim
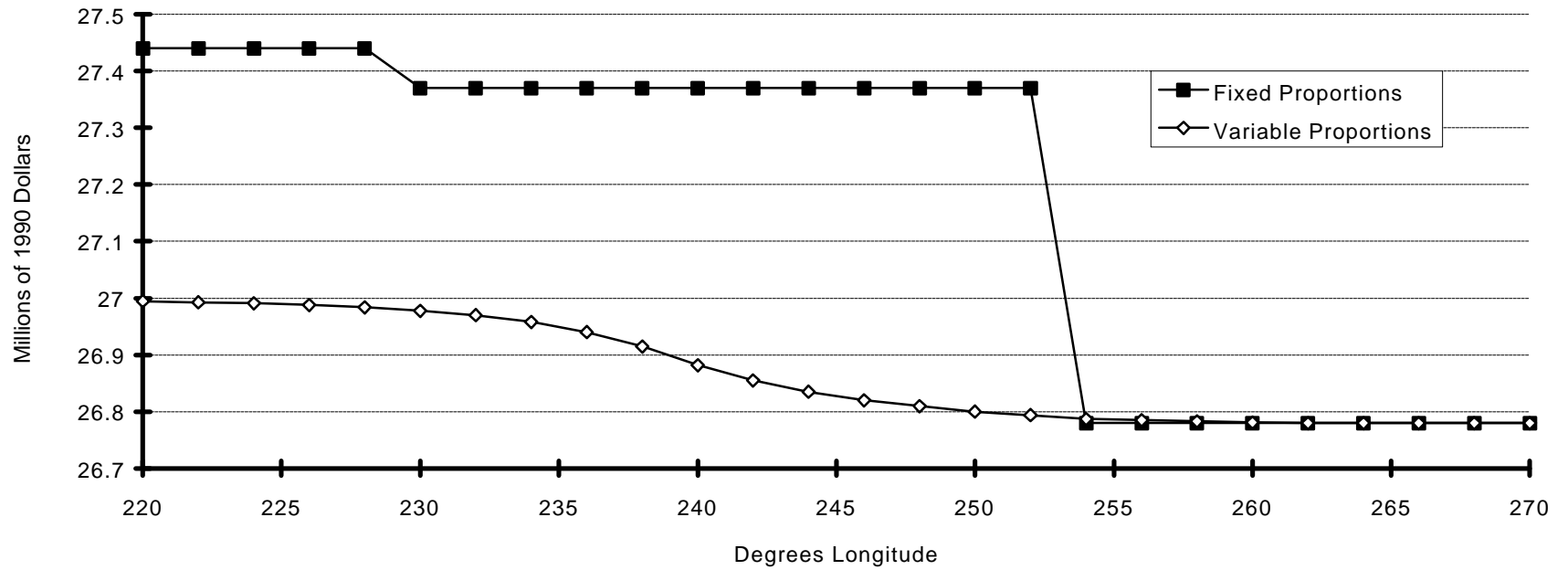
Figure 5. The Geostationary Orbit: The Estimated Cost Savings by Satellite Location for Countries in the Western Pacific Rim