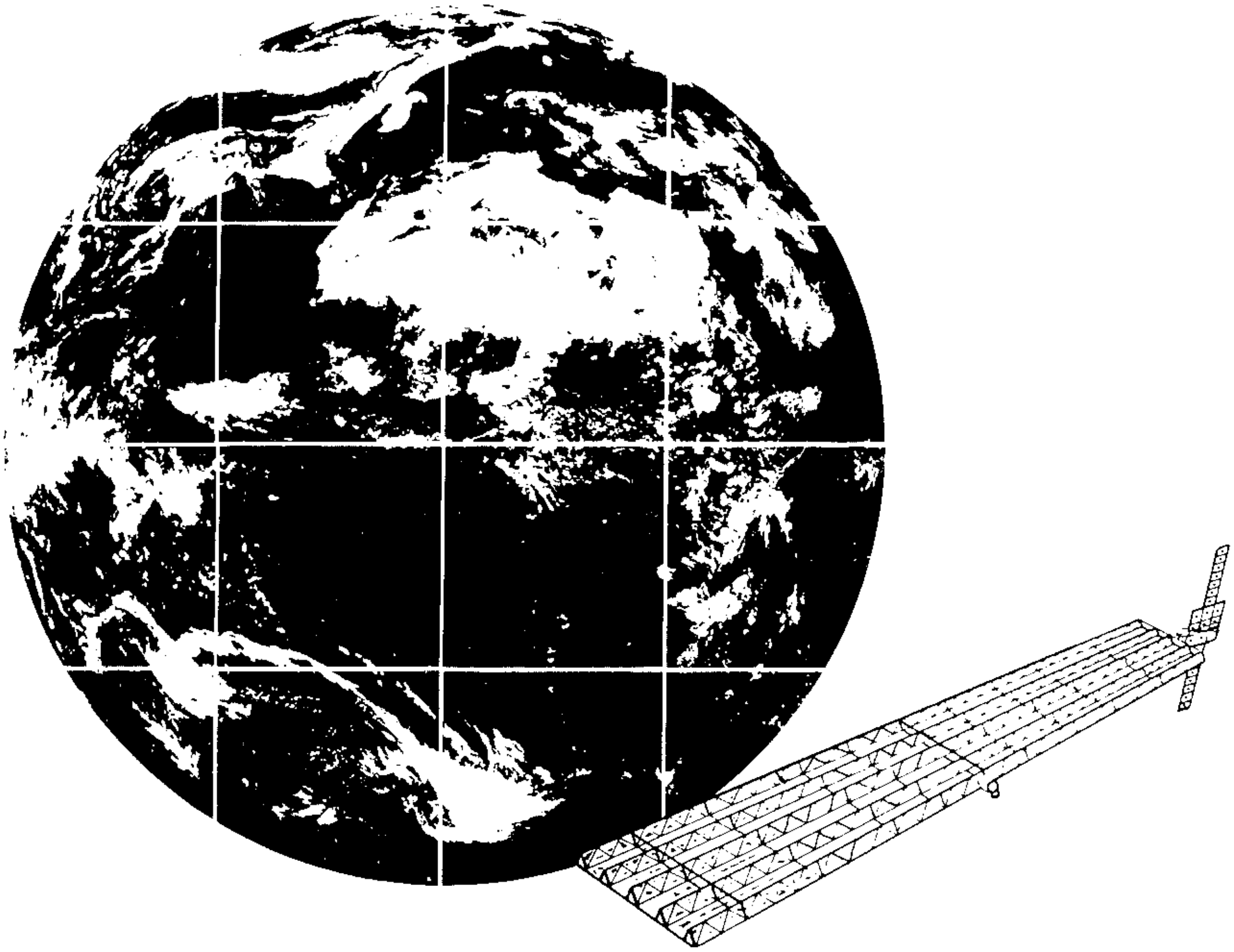
Volume 5, Number 3 1985

EARTH-ORIENTED APPLICATIONS OF SPACE TECHNOLOGY

Editor-in-Chief

L.G. NAPOLITANO University of Naples



Earth-Orient. applic. Space Technol. Vol. 5, No. 3, pp. 231 238, 1985
Printed in Great Britain

0277-4488/85 $3.00 + 0.00

ORBITAL DEBRIS MANAGEMENT: INTERNATIONAL COOPERATION FOR THE CONTROL OF A GROWING SAFETY HAZARD

DEAN OLMSTEAD
GTE SPRINT Communications Co. Burlingame, CA, U.S.A.

Abstract—Various policies have been proposed for controlling the growth of man-made orbital debris. It is now time to begin a detailed evaluation of the effectiveness and economic impacts of the proposed policies, and to develop the legal framework for supporting an approved policy. This paper first examines the increasing safety hazard of man-made orbital debris from the economic impact perspective. Increased safety for future users of the orbit is traded off against increased costs for today's users. Then an optimization model is proposed for determining the relative efficacy of several debris abatement policies and implmentation mechanisms. Finally, the impacts of other institutional considerations on the optimal policy selection are considered. Policy options will be evaluated on the basis of the incentives created for producers to adopt pollution abatement practices, the degree to which the policy preserves the orbit resource for future users, the acceptability of the policy to national administrations, and the impact of the policy on the cost of using the orbit resource as opposed to alternative technologies. This policy analysis is aided through the development of an optimization model. It is further shown that the selection of an optimal policy is sensitive to the relative cost of alternative technologies. Clearly, simply determining the economically optimal policy will not ensure its adoption, but the optimum will provide a benchmark for comparing the additional costs of a less than economically optimal policy with any "institutional" benefits associated with the adoption of such a policy.

ORBITAL DEBRIS PROBLEM DESCRIPTION

Introduction to the problem

Man-made orbital debris, though it exists in virtually all earth orbits, is of particular interest from the policy perspective at the geosynchronous altitude. This is due to the international interest in preserving this valuable and limited resource for all countries including those that do not currently, but may at some time in the future, have the technology to exploit the unique attributes of the geostationary orbit. The debris hazard appears to be monotonically increasing over time so that decisions made today relative to the use of the geostationary orbit will affect the quality of the resource for future users. Policy instruments exist for attaining a better intertemporal allocation of the safety hazard posed by the debris population, but mechanisms need to be developed for selecting the optimal alternative.

Physical characteristics of the problem

The most important characteristic of low earth orbits (LEO) from the policy perspective is that without active altitude maintenance an LEO satellite's orbit will eventually decay until re-entry occurs. This means that the LEO has a self-cleansing mechanism for orbital debris which can be taken advantage of in order to control the debris population. For all practical purposes, this natural control mechanism does not exist at the geostationary altitude.

Geosynchronous orbits average 35,787 km above the surface of the earth. At this altitude, a satellite's period is one siderial day, so the satellite crosses the equatiorial plane at the same longitude twice each day. If, additionally, the satellite's orbital plane is near zero inclination, the satellite is in a geostationary earth orbit (GEO) staying always over the same spot on the earth's surface. Use of the geostationary orbit as an input in the production of an information throughput capability has proven to be a cost effective method for providing many services. The GEO is used by all U.S. commercial communications satellites and many military communications satellites, as well as weather, tracking, navigation and data relay satellites; and the use of the GEO is increasing.

Typically these satellites have been designed for 3–10 year lifetimes and when their usefulness is ended they have been shut off and allowed to drift. Because of the distance from earth a satellite's orbit only decays about 1 km every 1000 years at the GEO altitude. This means that for all practical purposes, once an object has been placed in the GEO it will remain there throughout the relevant future. Thus, all expired GEO satellites and their attendant debris are still in the GEO, and the debris population will continue to grow monotonically as new satellites are launched and old ones cease operation. This points to an important difference with the LEO debris problem: policies which rely on self-cleansing of the orbit are not available for controlling GEO debris.

All services utilizing the GEO location produce orbital debris during three phases as a consequence of their production activities. The greatest addition to the existing debris population occurs during the satellite launch phase. The primary boost vehicle never reaches the GEO, but many smaller objects which are part of the launch process do. These include the orbital transfer vehicle, the apogee kick motor (used to circularize the orbit at the GEO altitude), payload shrouds, exploded restraining bolts and other miscellaneous ejecta. A satellite usually only contributes to the debris population during the course of its lifetime if it is fragmented by collision with debris or meteroids. But, at the end of a satellite's lifetime, it is typically shut off and left to natural forces, converting the entire satellite into hazardous debris.

Political characteristics of the problem

In 1976, 8 equatorial countries drew up and adopted the Bogota Convention, through which they claimed sovereignty over the segments of the geostationary orbit lying over their territories. While this agreement has not received broad international legal recognition, it provides an example of an age-old pattern which is now being adapted for space*. This pattern of establishing ownership over resources by whatever means are available and then trading the aquired resources for technology (or other goods and services) is also apparent in the International Telecommunication Union. (The ITU is an autonomous agency in the United Nations with responsibility for telecommunications matters including standards setting and the coordination of radio frequency spectrum uses.) The accepted procedure for establishing rights to spectrum resources has traditionally been the "first come, first served" principle. But growing concern amongst many countries (that the countries currently utilizing the space resources are monopolizing the geostationary orbit) is leading to efforts to "reserve" the orbit spectrum.

By virtue of its economic and technical advantages for communication systems, the geostationary orbit has proved so popular that its overcrowding has become a focus of attention. The crowding problem really has two distinct manifestations: (1) electromagnetic interference and (2) physical crowding. The electromagnetic interference aspect has received close scrutiny for many years, and is currently the binding constraint which limits the satellite capacity of the GEO. Improvements in technology and technology developments in higher frequency bands are constantly increasing this aspect of the orbit's capacity. But as the number of satellites in the GEO increase, so also will the physical crowding and collision hazard increase. Thus, while many countries are currently only concerned with the electromagnetic capacity of the orbit, the physical capacity is closely related so safety issues will receive increased attention in the future.

ORBITAL DEBRIS MARKET FAILURE

Existence of an externality

An externality exists when there are non-market interdependencies among economic activities. In the orbital debris problem, a negative production externality exists due to one non-market interdepency (the free disposal of debris within the geostationary orbit ring) with two time dimensions.

The first time dimension encompasses intratemporal effects. The production decisions of one orbit user do not take into account the impact of the production and disposal of orbital debris, i.e. the sum of the increases in all other producers marginal costs resulting from its actions. Thus there exists a discrepancy between today's private costs and today's social costs of the private actions.

The second time dimension exists because of the physical characteristics of the GEO. The growth of orbital debris in the GEO is monotonically increasing because no natural cleansing mechanism exists. However, the GEO is not precisely a depletable resource because there may exist some positive level of orbit resource usage and some level of debris abatement expenditures for which the orbit resource is not depleted (though its physical capacity will not increase). The absence of a natural renewal mechanism means that all future users of the GEO will be affected by all debris production and disposal decisions made in preceeding periods. Thus there also exists a discrepancy between current social costs and the intertemporal social costs of current social actions. That is, an allocation of the orbit environment which leads to an intratemporal optimum by matching current private costs with current social costs need not lead to an intertemporal optimal allocation of the environment.

The GEO is a common property resource

The orbit is used as both (1) a waste receptical for debris and (2) a location for providing an information throughput capability. Since no exclusion principles have been adopted (other than electromagnetic interference constraints) and a zero explicit price exists for these two uses of the orbit, the geostationary orbit exhibits the characteristics of a common property resource. While the traditional zero price for orbit usage makes the orbit appear to be a public good, meaningful ownership appears to be feasible. Thus, the orbit is not a pure public good and the optimal use of the orbit resource may be attainable through the establishment of "private" property rights.

The common-property status of the orbit and the accompanying zero marginal usage price result in the opportunity costs of using the orbit as an input (location) for production not being fully appreciated by each producer. The existence of any unrealized opportunity costs produces a discrepancy between private costs and social costs and a suboptimal allocation of resources. From the social perspective, the zero-priced orbit resource is over utilized, as is the associated production technology. Correspondingly, alternative resources and technologies (e.g. optical fibers) are underutilized†.

Without a market price for orbital use, the economic system does not include an automatic control mechanism for limiting the overuse of the orbit and the misallocation of related technologies. As a remedy, a property right for the orbit could be defined, perhaps in degrees of arc and kilometers of altitude. If exclusion were enforceable at a reasonable cost and the market operated perfectly, a scarcity price would be established. Presumably, this scarcity price would equal the opportunity costs of using the orbit and, in

---

*In the law of the Sea Treaty negotiations, countries established sovereign claims over as much as they were able to of the ocean, its contents and the ocean floor. This new "property right" can now potentially be traded for advanced technology.

†This misallocation also exists in the differential use of various orbital locations.

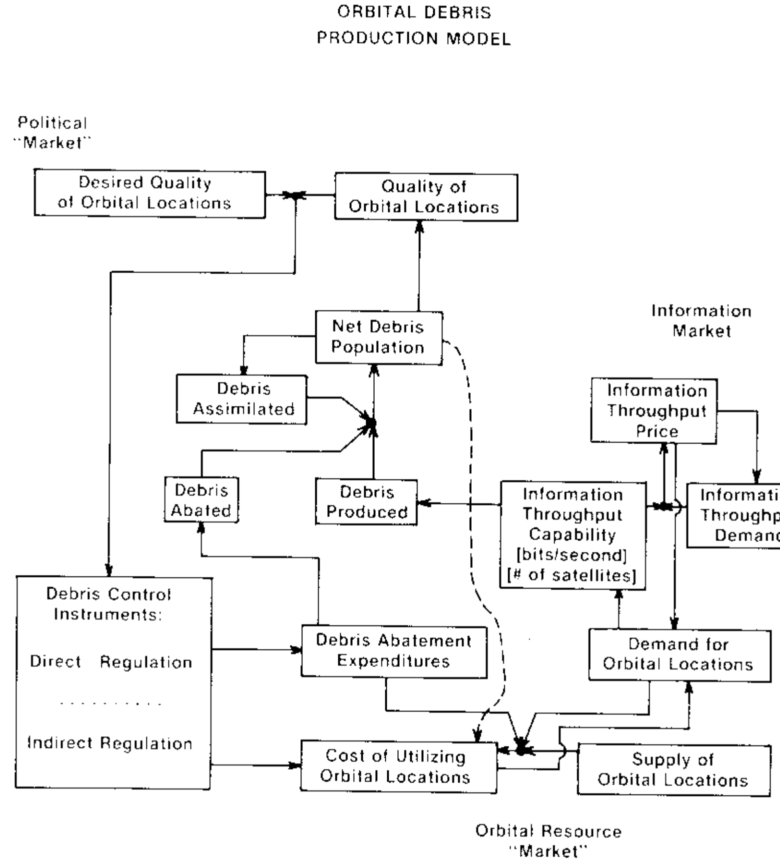


Fig. 1. Orbital debris production model.

O = total orbit available at a given state of technology
C_i = firm i's marginal cost of using the orbit
f_i = firm i's information throughput production function; $f_i = f_i\ (O_i,\ D)$
D_i = firms i's debris production function; $D_i - D_i\ (f_i\ (.))$
Da_i = firm i's debris abatement function
a_i = firm i's debris abatement expenditures
A = debris assimilation function
D = total net debris population
Q = quality of the orbit resource; $Q = Q\ (D)$
P_t = market price for information throughput in period t
Pd_t = market price for debris in period t
R_i = economic rent (profit) captured by firm i
R = aggregate economic rent for the industry

Basic model

Figure 1 illustrates the basic debris production system components and their interactions.

Static intratemporal model

The discrepancy between the price faced by the individual producer and the intratemporal socially optimal price for information throughput utilizing the orbit resource can be illustrated with a two firm, two input (orbit use, orbit quality), two output (throughput, debris), one period model.

Each firm has an objective function of the form

$$\operatorname*{Max}_{O_i} R_i = P^*f_i(D_i, D) - C_iO_i.$$

We have assumed functional forms such that the second order conditions for a maximum are satisfied and the first order condition is $P^*\mathrm{d}f_i/\mathrm{d}O_i = C_i^*$.

Within each period, society's objective is to maximize social welfare which is approximated in this case by the producers' aggregate profits.

$$\operatorname*{Max}_{O_1, O_2} R = R_1 + R_2 = P^*(f_1(O_1, D) + f_2(O_2, D)) - C_1O_1 - C_2O_2.$$

The second order conditons are again assumed to be satisfied and the first order conditions for social efficiency are

$$(P + P^*\mathrm{d}f_i/\mathrm{d}D^*\mathrm{d}D/Df_j)^*\mathrm{d}f_j/\mathrm{d}O_j = C_j.$$

We can see that the social price of the information throughput is lower than the private price (since $\mathrm{d}f_i/\mathrm{d}D < 0$) and the difference is the adverse effect of one producer's output of debris on the value of the other producer's throughput of information.

---

*Where $\mathrm{d}f_i/\mathrm{d}O_i$ is the partial derivative of f_i with respect to O_i.

If the basic policy instrument chosen is one of adjusting the price mechanism, the objective is to change each producers' incentives in such a way that their impact on the other producer is accounted for in their own objective function. Thus, if a tax on output is chosen, firm i's throughput should be taxed an amount $P^*\mathrm{d}f_j/\mathrm{d}f_i$.

If transaction costs were low relative to the value of the interfirm debris production impacts, side payments between the firms could be arranged which improve the allocation of the orbit resource. However, in the orbital debris case, there are many producers and the probability of collision is low, so the transaction costs are relatively high and the side payments which could lead to a social optimum are not being made.

Static intertemporal model

In order to illustrate the effects of debris production today on information throughput utilizing the orbit resource in the future, we can examine a two period model with one "aggregate" firm in each period, producing two outputs from two inputs.

Since we are examining only the intertemporal effects, the effects of debris produced within a period on production within a period will be omitted. The current firm's objective function is

$$\text{Max } R_1 = P_1{}^*f_1(O_1) - C_1O_1$$

and the first order condition is $P_1{}^*\mathrm{d}f_1/\mathrm{d}O_1 = C_1$. The future firm's production is impacted by the current firm's production of debris, so its objective function is

$$\text{Max } R_2 = P_2{}^*f_2(O_2, D_1) - C_2O_2$$

Since, from the perspective of the future firm, the debris population is an exogenous factor, the first order condition is $P_2{}^*\mathrm{d}f_2/\mathrm{d}O_2 = C_2$.

Ignoring discounting, by assuming that society values both periods equivalently in the current period, the social objective function is

$$\underset{O_1O_2}{\text{Max}}\ R_1 = P_1{}^*f_1(O_1) + P_2{}^*f_2(O_2, D_1(f_1)) - C_1O_1 - C_2O_2.$$

From society's perspective, the debris population in the future period is endogenous, so the quantity of debris produced can be chosen at an optimal level. The first order conditons are

$$\mathrm{d}R/\mathrm{d}O_1 = P_1{}^*\mathrm{d}f_1/\mathrm{d}O_1 + P_2{}^*\mathrm{d}f_2/\mathrm{d}D_1{}^*\,\mathrm{d}D_1/\mathrm{d}f_1{}^*\mathrm{d}f_1/\mathrm{d}O_1 - C_1 = 0$$

$$\mathrm{d}R/\mathrm{d}O_2 = P_2{}^*\mathrm{d}f_2/\mathrm{d}O_2 - C_2 = 0.$$

As in the intratemporal case, there is a difference between private price and social price equal to the value of the impact on one firm of the other firm's production of debris. In this case, a socially efficient allocation of resources would result from a tax on the current firms output equal to $P_2{}^*\mathrm{d}f_2/\mathrm{d}f_1$. However, there does not exist the possibility for side payments leading to an optimum as there was in the first case. This is because, no matter how large the value of the debris impact, the transaction costs will be higher. Without a representative in the current period, no substantial mechanism exists for future firms to negotiate with current firms.

Combining the results from these two cases and generalizing to n firms, the first order conditions for maximal social profits over two periods indicate that the intertemporal socially optimal tax on firm i's throughput should be set at

$$\sum_{j \neq i}^{n} (P_1{}^*\mathrm{d}f_j/\mathrm{d}f_i) + \sum_{k \neq i}^{m} (P_2{}^*\mathrm{d}f_k/\mathrm{d}f_i).$$

In order to actually compute this tax, we need the marginal effect of debris production on throughput at the optimal level of production. This is an empirical problem which is being modelled at NASA's Johnson Space Center.

Another simple extension we can make to these models is the adverse impact of orbital debris on the costs of using the orbit resource. Increased costs might arise from the need for redundant operations or increased shielding. A firm's objective function now has costs as a function of the total debris population.

$$\text{Max } R_i = P^*f_i(O_i, D) - C_i(D)^*O_i$$

and the first order condition is

$$P^*\mathrm{d}f_i/\mathrm{d}O_i = C_i(O) + \mathrm{d}C_i/\mathrm{d}D^*\mathrm{d}D/\mathrm{d}O_i{}^*O_i$$

where the last term is the increase in the cost of using the orbit resource per unit increase in orbit usage.

Again, externalities exist because the production decision of one firm does not account for the impact its production of debris will have on the costs of other firms. Incorporating debris dependent costs into the social objective function (and ignoring intertemporal and production effects) results in the first order conditions for a maximum being

$$P^*\mathrm{d}f_i/\mathrm{d}O_i = C_i(D) - \sum_{i}^{n} (\mathrm{d}C_j/\mathrm{d}D^*\mathrm{d}D/\mathrm{d}O_i{}^*O_j).$$

Since costs increase with increased debris: $\mathrm{d}C_j/\mathrm{d}D > 0$, for all j; and we know that $\mathrm{d}D/\mathrm{d}O_i > 0$, for all i; we have, therefore, that the cost upon which firm i bases its orbit utilization decision is less than the social cost of its use of the orbit by

$$\sum_{j \neq i}^{n} (\mathrm{d}C_j/\mathrm{d}D^*\mathrm{d}D/\mathrm{d}O_i{}^*O_j)$$

which is the impact firm i's decision has on the orbit utilization costs of all other firms.

Effect of alternative technologies

The models discussed above do not provide any insight into the conditions for a general equilibrium which should be examined because changes in relative "commodity" prices will affect more than just the orbit users. A debris (or orbit utilization) tax, a change in property rights, or any other policy instrument which alters the prices producers face, will

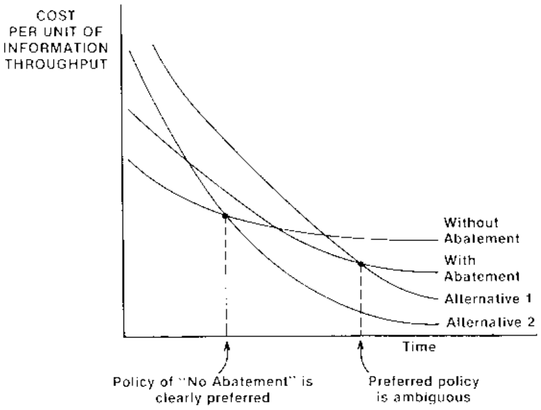


Fig. 2. Effect of alternative technologies (e.g. optical fibers) on preferred policy.

change the cost of providing an information throughput capability which utilizes the orbit relative to the cost of other methods of providing the service. This shift in relative costs will affect the allocation of resources and the industry's structure.

Figure 2 illustrates the importance of the relative costs of alternative technologies in the selection of an optimal policy. In the example given in Fig. 2, two possible cost paths over time are given for a technological alternative to utilizing the orbit resource*. The cost of using any of the technologies is shown as decreasing over time. If the cost path is as indicated by Alternative 2, then a policy which requires no abatement, such as the *status quo*, is clearly preferred. This is because producers will switch to the lower cost production technology before any benefits can be realized from adopting an abatement policy which results in higher near-term costs. If the cost path follows Alternative 1, the preferred policy is ambiguous. Adopting an abatement policy results in a period of lower costs than a no-abatement policy, but the cost advantages in this period may not outweigh the cost disadvantages in the earlier periods.

The conditions in this example may arise in actuality and they point to a potential conflict between the Fixed Satellite Service (FSS) operators and the Broadcast Satellite Service (BSS) operators, if the choice of a debris abatement policy ever occurs. Optical fibers are rapidly decreasing in cost and they provide a feasible alternative to the FSS but not the BSS. The BSS operators' interests in the orbit may extend many years further than that of the FSS operators. Therefore, if a choice of abatement policies arises, the FSS operators may prefer a no abatement policy while the BSS operators may prefer abatement.

CONCLUSIONS

The simple models presented here provide only the flavor of a more complete specification of the orbital debris management problem. The models are not intended to indicate that any debris control policy should be enacted. However, they should underscore the importance of understanding the tradeoff between current costs and future safety being made implicitly in satellite systems design and operation decisions. More sophisticated economic models are being developed which incorporate uncertainty, risk preferences and the dynamic nature of the optimal solution. These economic models, able to draw on the continually improved information coming from empirical investigations and physical modelling efforts, will provide guidance in the selection of an optimal policy to control a growing international safety hazard.

REFERENCES

1. American Institute of Aeronautics and Astronautics Technical Committee On Space Systems, Space Debris—An AIAA Position Paper (1981).
2. V. A. Chobotov, Collision hazard in space. *J. Astronaut. Sci.* **XXX,** No. 3, (1982).
3. J. H. Dales, *Pollution, Property and Prices.* University of Toronto Press, Toronto (1968).
4. M. D. Intriligator, *Mathematical Optimization and Economic Theory.* Prentice-Hall, Englewood Cliffs, NJ (1971).
5. D. J. Kessler, Sources of orbital debris and the projected environment for future spacecraft. *J. Spacecraft Rockets* **18,** No. 4, (1981).
6. H. J. Levin, Regional versus global strategies in orbit spectrum management: the global commons revisited. *AEA Proc.* (1982).
7. D. A. Olmstead, The international context for orbital debris: UNISPACE '82 and the ITU. *Orbital Debris Workshop Proceedings* (Edited by D. J. Kessler). Johnson Space Center, Houston, TX (1982).
8. H. Siebert, *Economics of the Environment*, Lexington Books, Lexington, MA (1981).
9. M. G. Wolfe, V. A. Chobotov and F. E. Bond, Manmade space debris—implications for the future. *Earth Orient. applic. Space Technol.* **3,** 19–29 (1983).

---

*The actual cost path is unknown but can be forecasted.

FI

¹Head

Abstra
by Spa
retrieva
investig

ESA's Membe
opment of a r
of experiment
perimentation
gravity) enviro
Carrier, or Eu
launched on it
Shuttle. It wil
after some six
first of a serie
missions, plan
yearly interval

THE S

Approximat
tons, Eureca w
equipped, it w
Shuttle's carg
with a high de
in mind, and
accommodate
beyond those

Eureca will
comparable n

—structural in
—thermal con
—power gener
—data manag
—attitude con

EARTH-ORIENTED APPLICATIONS OF SPACE TECHNOLOGY

Volume 5, Number 3 **1985**

CONTENTS

Owen K. Garriott and Daniel B. DeBra	161	A simple microgravity table for the orbiter or space station
J. Andersson	165	VIKING—a low cost scientific satellite description and test results
S. Sonoyama, M. Nagatomo and T. Yamanaka	175	Japanese mission model for space station
Yasushi Horikawa and Hideo Ohba	185	Studies on Japan's Earth Resources Satellite—1
T. Hajós, G. Büttner, F. Csillag and A. Szilágyi	193	Satellite image processing for a small country: the Hungarian case
T. Iwata	201	Flying railway—a mean for orbital transfer
John J. Neilon	207	Processing cargoes for the first two operational STS flights at KSC
Kyoichi Kuriki, Makoto Nagatomo, Haruyuki Okuda and Tatsuo Yamanaka	221	Japanese free-flying satellites
Dean Olmstead	231	Orbital debris management: international cooperation for the control of a growing safety hazard
G. Seibert and A. Hahne	239	First payload for the European retrievable carrier Eureca
L. Perek	247	Management of outer space
Keiji Nitta and Masamichi Yamashita	253	Concept study on the technology of CELSS

Earth-Orient. applic. Space Technol. is
indexed/abstracted in Current Contents,
Cambridge Scientific Abs., Engrg. Monthly & Author Index,
World Aviation Directory

ISSN 0277-4488
EAOTDY 5(3) 161-263 (1985)

Printed in Great Britain by A. Wheaton & Co. Ltd, Exeter