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Background paper

IMPACT OF SPACE ACTIVITIES ON THE EARTH AND SPACE ENVIRONMENT

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PREFACE

The United Nations General Assembly decided to convene the Second United Nations Conference on the Exploration and Peaceful Uses of Outer Space in Vienna, Austria, from 9 to 21 August 1982.

As part of the preparation for the Conference, a series of background papers have been prepared by the Secretariat with the assistance of non-governmental organizations of universal membership and specialized agencies and other organizations of the United Nations system. The purpose of these papers is to provide a factual summary of the current state of space activities and to assist Member States in the preparation of their national papers. The papers cover general questions, specific technical issues, socio-economic aspects and international co-operation.

This paper is one of four concerning general questions. It was prepared with the assistance of an international team of experts organized by the Committee on Space Research (COSPAR) established by the International Council of Scientific Unions (ICSU). For chapters I, II, III and V, the team was composed of: Prof. K. Rawer (Federal Republic of Germany), Chairman; Dr. K. S. W. Champion (United States of America), Prof. A. P. Mitra (India), Prof. E. A. Müller (Switzerland), Prof. W. Riedler (Austria), Dr. M. J. Rycroft (United Kingdom of Great Britain and Northern Ireland), Prof. G. A. Skuridin (Union of Soviet Socialist Republics), Executive Members; Dr. R. E. Barrington (Canada), Dr. J. Baumgardner (United States), Dr. A. P. Bernhardt (United States), Mr. J. P. Chassaing (France), Dr. L. H. Doherty (Canada), Dr. R. D. Eberst (United Kingdom of Great Britain and Northern Ireland); Dr. J. C. Gille (United States), Dr. B. H. Grahl (Federal Republic of Germany), Prof. S. Hayakawa (Japan), Dr. F. Horner (United Kingdom of Great Britain and Northern Ireland), Dr. J. A. Klobuchar (United States), Dr. F. A. Koomanoff (United States), Dr. H. Martinides (European Space Agency (ESA)), Prof. M. J. Mendillo (United States), Dr. C. M. Minnis (United Kingdom), Dr. C. T. Russell (United States), Prof. S. M. Siegel (United States), Prof. F. G. Smith (United Kingdom of Great Britain and Northern Ireland); Prof. M. S. Vardya (India), Prof. R. Wielebinski (Federal Republic of Germany), Dr. P. Wilson (Federal Republic of Germany), Contributors. For chapter IV, the team was composed of: Dr. L. Bankov (Bulgaria), Dr. Z. Dachev (Bulgaria), Dr. A Gdalevitch (Union of Soviet Socialist Republics), Dr. M. Gogoshev (Bulgaria), Dr. D. G. King-Hele (United Kingdom), Dr. I. Kutiev (Bulgaria), Dr. P. Lála (Czechoslovakia), Dr. Yu. Matviichuk (Union of Soviet Socialist Republics), Prof. G. Moraitis (Greece), Prof. L. Perek (Czechoslovakia), Dr. I. Podgorny (Union of Soviet Socialist Republics), Dr. M. J. Rycroft (United Kingdom of Great Britain and Northern Ireland), Dr. L. Sehnal (Czechoslovakia) and Prof. K. Serafimov (Bulgaria). Apart from the writers, an even greater number of scientists have helped with advice or criticism.

The purpose of this paper is to examine some of the possible effects on the earth and space environment of space activities, and to suggest means by which undesirable effects might be minimized. The report considers the possible impact of the introduction of new material, either deliberate or accidental, into the earth or space environment, and the possible physical, chemical or biological consequences.

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INTRODUCTION

1. In the course of his day-to-day existence, man has always been obliged to submit himself to dangers of different kinds, and to run the risk of being involved in accidents. However, since he is aware of the dangers, and can often measure the probability of their occurrence, he normally takes precautions designed to eliminate accidents, or at least to limit the risk if complete elimination is not possible for economic or other reasons. In considering the dangers associated with space activities, it may be relevant to consider the way in which we deal with the risks associated with, for example, air and surface transport systems, or fire in buildings. Because of the very high exposure of populations to these dangers, many accidents actually occur and, in consequence, it is possible to identify their causes and to take appropriate steps to reduce the risk.

2. In space activities generally, the numbers of individuals exposed to the various risks are very small in comparison with those exposed to transport accidents. Hence, the number of accidents has been small. However, it is possible to envisage accidents that have never occurred, but that could conceivably occur even though they may be very unlikely. From the beginning of the space era, scientists and engineers responsible for the research programmes have tried to assess the real and potential dangers and have taken, or have proposed, appropriate measures designed to eliminate or to minimize the risk of accidents.

3. Quite apart from the small risk of accidents to individuals engaged in space activities, there is also a potential risk of damage to the terrestrial environment. For example, certain gases emitted from space vehicles and their rocket engines could change the protective power of the atmosphere as a shield against harmful solar ultra-violet radiation, or they could modify the reflecting properties of the ionosphere which is an important element in radio-communications.

4. Space activities could also have undesirable effects for other branches of scientific research. Very large numbers of artificial satellites, each emitting infra-red radiation or radio waves or reflecting sunlight, would obviously be of concern to astronomers. Also, widespread contamination of the upper atmosphere and the magnetosphere would hinder studies of the natural state and composition of these regions and research on the origins of the earth itself.

5. It must be emphasized that in many cases it is not possible to assess with any accuracy the size of the risk. The type of precaution that needs to be taken to minimize a given task depends on the nature of the risk itself and its possible consequences, on the probability that the risk will actually lead to an accident, and on the economic consequences of the possible precautions. It cannot be excluded, of course, that new developments may occur which would change the situation considerably.

I. POSSIBLE ENVIRONMENTAL EFFECTS OF LAUNCH AND RE-ENTRY

A. Launch site

6. A rocket launching produces a so-called "ground cloud" consisting of exhaust gases, cooling water, sand and dust (figure 1). Generally, the resulting air pollution is limited both in extent and intensity, and the current level of satellite launchings poses no extensive danger.

7. If launching activities increase greatly, however, the possible effects may have to be re-examined. In particular, if solar power satellite (SPS) systems were developed, consisting of perhaps 60 satellites, each with 50 sq km of solar panels, the cumulative launch effects, on air and water quality around the launch site, might be significant.

8. Given the unusual size of the SPS launching rockets, the risk of accidents and other undesirable effects is greater than for more conventional rockets. The fueling of the rockets will demand large volumes of liquid hydrogen and other explosive or inflammable liquids, and there are obvious risks during the transport of these materials to the launch site and during their transfer into the rocket fuel tanks. Spills of these liquids resulting from accidents could cause damage to life and local damage to ecosystems. The explosive potential of an SPS rocket will be about twice that of the Saturn V used for moon launches; this implies that structural damage could be caused to buildings at distances of the order of tens of kilometres in the case of a catastrophic explosion.

9. The noise levels generated during SPS operations would be high, and it seems possible that the 24 h average limits specified by the United States Environmental Protection Agency would be exceeded, not only because of the high noise produced by each rocket, but also because there will be several launches per day. More detailed studies of this question are required. In addition to the noise generated by the rocket motors, there will also be sonic booms during the ascent and re-entry of the rockets. These are liable to startle humans and animals and might also cause structural damage.

B. Upper atmosphere

10. More extensive atmospheric contamination is produced as the rocket engines continue to burn up to altitudes between 100 and 200 km. The magnitude of the contamination depends on the amount of propellent burned which depends on the mass of the vehicle and the altitude of the desired orbit. For larger rockets, the total amount of matter introduced into the atmosphere can be quite substantial; for example, during one launch of the space shuttle about 1 million kg of solid propellant are burned in the boosters and 750,000 kg of hydrogen/oxygen in the main engine.

11. At altitudes above 20 km in the stratosphere, and even above 60 km in the mesosphere, significant effects due to injection of water and nitrogen oxides could occur when very large vehicles are launched. Since atmospheric density decreases rapidly with height, the sensitivity of the atmosphere increases drastically with increasing altitude. Thus, not only exhaust during propulsion must be considered, but also the outflow of gases from the combustion chamber after the engines have been shut off.

12. Because of deficiencies in our understanding of physical and chemical processes above 40 km, especially with regard to the effects of water vapour, all theoretical predictions suffer from a significant uncertainty. Potential effects on cloud formation by mesospheric water release, for example have yet to be assessed.

13. Possible effects of stratospheric contamination include changes in the ozone (O_3) layer which shields the surface from harmful ultra-violet radiation. The amount of ozone in the layer is determined by chemical reactions which could be disturbed by changes in the concentration of gases already present such as carbon-dioxide, or by the introduction of other substances such as chlorine compounds.

14. The large solid-fuel rocket engines to be used in the Space Shuttle, for example, release chlorine and hydrogen chloride. Calculations, assuming a maximum of 60 launches per year, have indicated that the ozone content of the atmosphere would be reduced by less than 0.5 per cent, an effect less than that due to other natural or man-made causes. Studies of other vapours released by the Space Shuttle suggest an insigificant effect.

15. A satellite in low earth orbit gradually loses energy and altitude due to the small resistance of the thin atmosphere. At an altitude of about 100 km, the resistance starts to rise rapidly, and the satellite descends quickly into the atmosphere. During this "re-entry", a very high temperature is reached at the leading edge of the vehicle, and generally the satellite disintegrates and vaporizes in the upper atmosphere. The resulting production of metal vapours and oxides could influence the balance of electrically charged constituents (ions) and, locally at least, change the ionospheric conditions that affect radio communication. Exotic elements such as beryllium and cadmium may be of particular concern. At present, however, it appears that meteorites, aircraft and terrestrial sources introduce much greater quantities of material than satellite re-entry. The total meteoric mass entering the atmosphere, for example, is estimated at 10,000 kg/day. In the future, if large numbers of satellites were allowed to burn out on re-entry, the resulting contamination of the upper atmosphere might become important. Most future large vehicles, however, such as the Space Shuttle will be controlled during re-entry.

II. IMPACT ON THE ORBITAL ENVIRONMENT

A. Operational releases

16. At orbital altitudes, above 100 km, the atmospheric density is so low that very small quantities of material may have significant environmental effects. The rocket engines have usually been shut down well before the satellite reaches altitude, but other releases occur as part of orbital operations. These releases include outgassing of spacecraft materials, propulsion for attitude control and station-keeping, liquid from cooling systems and, in the case of manned vehicles, leakage of vehicle atmosphere.

17. For the Shuttle Orbiter, detailed model calculations have been made concerning the different release sources and their importance. The results are summarized in the following table:

Major Shuttle Orbiter release sources

Source	Duration	Flow-rate (approx.)	Constituents
Outgassing	continuous	10^{-4} kg d^{-1}	hydrocarbon, chain fragments, other volatiles
Offgassing	continuous for first 100 h in orbit	10^{-3} kg d^{-1}	water, light gases, volatiles
Evaporator	as required	10 kg h^{-1}	water
Cabin leakage	continuous	3 kg d^{-1}	O_2, N_2, CO_2, H_2O
Thrust engines	as required	0.04 kg min^{-1}	H_2O, N_2, H_2, CO, CO_2, H

Water release by the evaporator, which might eject up to 140 kg per day, represents probably the most important impact on the atmosphere during a Shuttle flight. Cabin leakage can be expected to be harmless, while the thrust engines would only locally disturb the environment - with potential impact on a few on-board experiments.

18. Among the chemical reactions following the in-orbit releases, those concerning the ionosphere have been studied in detail. This is the region above 60 km where free electric charges (negative electrons and positive ions) exist in large quantities due mainly to the impact of ultra-violet and X-ray radiation from the sun. The peak charge density is reached at altitudes of about 250 to 400 km. While the numerical density of neutral species is much larger, the ionospheric

electrons are of great importance for radio communications since waves in the high frequency (HF) range are normally reflected from the ionosphere back to the ground, so that by multiple reflection, in spite of the curvature of the earth, they may reach very large distances. Reflection occurs also at lower frequencies down to ELF (extremely low frequency). Waves of much higher frequencies (VHF, UHF) penetrate the ionosphere, but suffer from changes in polarization and even direction. These effects decrease with increasing frequency, so that the importance of the ionospheric influence is very small in the UHF range. However, advanced systems for radio direction-finding and navigation and, in particular, the so-called "very long base-line interferometry" (VLBI) which achieves enormous accuracy, still suffer most from the variable ionospheric influence, even when using UHF waves.

19. The preservation of the ionosphere in its normal state, therefore has considerable practical importance. Under natural conditions, positive and negative charges recombine and so disappear in a rather complicated ion chemistry 1/ which can be largely changed by the introduction of small amounts of interfering species not normally present in the upper atmosphere. Of particular concern are carbon and nitrogen oxides, most organic molecules and unburned fuel, because these molecules become attached to electrons and hence form negative ions. Water vapour, if present, also removes a lot of electrons by catalyzing their recombination with positive ions. This increased removal of electrons, results in a drastic change in the reflecting properties of the ionosphere for radio waves, and for other radio wave propagation phenomena. Thus, species produced in rocket exhausts and during re-entry may provoke large local changes, particularly in the lower ionosphere. Detailed observations were made with the 1973 SKYLAB launch of the National Aeronautics and Space Administration (NASA): the zone of depleted electron density covered an area 2,000 km in diameter lasting (at peak altitude) for several hours. The phenomenon, which must justly be called a "big hole" in the ionosphere, had important effects on radio communication.

20. The most important case which was studied in detail was the launch with an Atlas/Centaur thruster of the HEAO-C satellite in 1979. While usually the upper stage is shut down below 200 km, in that case it was ignited only at 209 km and kept burning up to 466 km. Large deviations from normal radio propagation were observed, in particular with satellite beacons. Even larger thrusters are now being discussed, for example in conjunction with the solar power satellite (SPS) project. These "heavy launch vehicles" would have 150 times the payload capabilities of the Atlas/Centaur combination. It must, therefore, be stated that each launch of a larger space vehicle produces a major regional disturbance in the ionosphere, which may last several hours. Ionospheric effects, though of smaller extent, are also expected during re-entry, as a consequence of the burn-out and vaporization products that are produced.

21. The deliberate removal of satellites from orbit at the end of their usual lifetimes, as has been suggested to relieve congestion in orbit, might have substantial environmental consequences. The most effective means of removal, braking by retro-firing, would result in considerable fuel being burned at

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1/ See background paper No. 1, "Current and future state of space science" (A/CONF.101/BP/1).

orbital altitude. At an altitude of 1,500 km, the required propellant mass would be about 10 per cent of the satellite mass. "Clean" propellants would be most desirable, but no such solution is yet in sight.

22. In addition to the effect of releasing material, an inverse effect, namely the collection of particles from the environment is expected from satellites of larger size, in particular those with large metallic structures such as extended antennas, when they sweep through the outermost atmospheric regions where charged particles are predominant, i.e. in the plasmasphere and magnetosphere. They may also provoke artificial electric and magnetic fields as a result of motion relative to the earth's magnetic field and the accumulation of ions.

B. Release experiments

1. Effects on chemical composition

23. Artificial releases of chemically reactive substances are a valuable tool of space research. Light metal vapour, e.g. sodium, barium or strontium, has often been released into the upper atmosphere as a "tracer". The vapour column, when illuminated by the sun, can be optically observed; and, by triangulation, winds in the upper atmosphere can be unambiguously determined. Barium and strontium are largely ionized by solar ultra-violet radiation, so that charged particles are formed which can also be identified by the specific colour of the light they emit. Thus, the motion of charged clouds becomes observable. Electric fields in the upper atmosphere were so determined, and this information is of particular importance for understanding the phenomena occurring in the ionosphere at high latitudes. Outside the terrestrial environment, releases have been made to simulate natural comets.

24. Other releases are undertaken for studies of chemical reactions occurring naturally in the upper atmosphere, with the intention of using this particular environment as a laboratory where much higher cleanliness is achieveable than in any terrestrial laboratory. Finally, releases have also been undertaken with the deliberate objective of changing the properties of the ionosphere, so as to improve or impair radio wave propagation by the ionosphere.

25. Such artificial releases are certainly an important tool for scientific studies. On the other hand, the question arises as to whether such activities might provoke unintentional changes that could not be reasonably foreseen, for example, long-lasting or extended deterioration of the natural environment, disadvantages for other scientific activities such as astronomy, geophysics, etc. The ejected masses have been small in most scientific experiments undertaken until now; nevertheless, noticeable atmospheric changes have sometimes occurred, in particular in connexion with the ion-chemistry for the charged species. Since there is a tendency for the loads released to increase, some limitations on such experiments may be needed in the near future.

26. In order to estimate the potential detrimental effect of releases, the associated kinetics have been studied in great detail. A quantity of neutral gas,

when released into a tenuous atmosphere, expands rapidly by the conversion of thermal into kinetic energy, and thus drops rapidly in temperature. The temperature decrease at the beginning of the release is particularly steep in a rarified atmosphere. The cooling can be so strong that condensation vapours and even droplets may occur for a short while. Condensation starts around any suitable "nucleus", e.g. dust particles, charged particles (ions), or clusters of gas ions. All this occurs during the first second after release. Subsequently, the expanded gas cloud is heated up by the ambient atmosphere with the evaporation of the condensed droplets. After about 10 s the ejected gas has reached about 1 km distance and diffuses steadily into the atmosphere, the speed of further expansion depending on the molecular weight of the gas, and on the atmospheric density at the level of ejection. Particularly great diffusion speeds occur with hydrogen. As a consequence of gravity, the long-term expansion is larger in horizontal directions than downwards. Gas clouds released at high initial velocity produce very asymetric patterns and may cover a 100 km horizontal range in about 15 s.

27. Kinetic effects dominate the release processes only during the first minute or so. The subsequent development depends on whether chemical reactions become important or not. If not, the released matter is further diluted by diffusion into the atmosphere with a propagation speed that is higher at greater altitudes. The removal of the injected material depends essentially on its downward propagation, which can be astonishingly slow even for constituents of large molecular weight. Of the light gases, only hydrogen is able to go upwards and eventually leave the atmosphere in the direction of the magnetosphere. Most injected gases or vapours, though dilated, may remain for months in the upper atmosphere. In some case chemical reactions may determine the fate of the injected material. Above 100 km, highly reactive atomic oxygen is present and oxidation may occur extremely rapidly. The creation or transformation of unusual substances by unusual chemical reactions is a complex field in which much work is required before conclusions can be safely drawn.

28. Astronomical and geophysical observers are often interested in optical phenomena of extremely weak intensity which can easily be disturbed by unusual species deposited in the atmosphere; for example, the yellow emission of sodium light in the atmosphere has been used to estimate the natural over-all meteoric activity. Releases, when frequently made, may introduce comparable amounts of sodium and so endanger such observations. Moreover, conclusions about the origin of our atmosphere may become invalid if the natural or artificial origin of some minor constituent is doubtful.

2. Effects on ion and electron concentration

29. Detailed studies exist of ion-chemistry reactions occurring after releases. Considerable changes in the natural conditions in the ionosphere have been produced in systematic experiments carried out in the 1960s and 1970s. The release of various species has caused slight increases or, more commonly, substantial decreases in electron density. In contrast to the behaviour of neutral

constituents, the effects on electrons and ions normally disappear in hours or a day. Only at very high altitudes, above 2000 km, are longer lasting effects likely to occur.

30. If metal vapour is released, it is often easily ionized by sunlight so that free electrons and positive ions are produced. For certain species (like sodium, barium or strontium) the energy needed for this transformation is much smaller than for normal air molecules. These ions therefore do not as easily recombine with electrons; thus they have a much longer lifetime and increase the total electron density.

31. Plasma depletion, i.e. large-scale reduction of the electron density in the ionosphere can be provoked by the release of quite different gases. For example, water vapour, hydrogen, nitrogen dioxide (NO_2) and carbon dioxide (CO_2) all have a similar efficiency in decreasing the lifetime of O^+, the main ion in the upper atmosphere: a 1 per cent concentration of these (compared with atmospheric nitrogen) decreases the lifetime by a factor of 10. Nitrous oxide (N_2O) is less efficient and the factor is only 3. A very strong effect upon the vertical profile of electron density was obtained by a model computation for a release of 100 kg of hydrogen at 300 km altitude. The sequence of computed profiles reproduced in figure 2 shows a reduction of the peak electron density by about a factor of 3, lasting for more than one hour. The ion temperature decreases but the electron temperature is drastically increased, by 1500°K, 10 minutes after the release. At the same time the hole created in the ionosphere (see figure 3) is about 250 km wide. The disturbance propagates upwards since hydrogen ions move up in a tube along the lines of the magnetic field of the earth.

32. Such changes strongly effect radio wave propagation. In particular, the trajectories along which an HF wave travels can be seriously deformed. Waves otherwise reflected in the ionosphere may escape through the hole. For those reflected in the disturbed region, strong deviations from the usual "great circle propagation" may occur with the result that direction finders give wrong indications. Waves may also be guided in the hole and so take a direction quite different from the usual one. This can, in particular, happen in the plasmasphere (above 200 km) for very low frequency (VLF) waves. Such effects can be used for studying interactions between charged particles and very long waves - experiments which could never be carried out in a laboratory. A very particular "application" has been proposed in order to increase temporarily the intensities, at ground level, of frequencies used in radio astronomy, i.e. the use of the hole as a lens for radio waves, which would focus VHF radiation arriving from extraterrestrial sources.

33. The first successful depletion experiment in 1977 detonated 88 kg of high explosive at 261 km altitude, eventually producing water vapour and carbon and nitrogen oxides in large quantities. Rocket- and ground-based instruments recorded not only a decrease in electron concentration, but also changes in the chemical composition of the ion population, and an increased airglow. In order to produce an artificial "hole" in the ionosphere 3000 kg of rocket propellant will be burned during the second SPACELAB mission, probably in 1982. Scientifically, depletion experiments are an important tool for measuring chemical and diffusion coefficients

directly in the "ionospheric laboratory", since they allow determinations to be made which, because of impurities, cannot be made in terrestrial laboratories. Further, such experiments allow particular effects in radio wave propagation to be studied experimentally, e.g. ducting of waves in the HF or VLF ranges. The spectrum of the airglow artificially produced at the release can give information about the chemical and physical processes in the modified ionosphere.

34. Such depletion experiments have shown that, by this technique, drastic alterations of the natural conditions in the ionosphere can be artifically produced. Lowering of the electron density by 90 per cent and raising the electron temperature by a factor of 10 can be achieved locally. Drastic effects on radio wave propagation were observed during such experiments. Fortunately, there is a rapid "healing power" which, even for the plasmasphere, limits the duration of the artificial depletion to several hours.

35. A comparison of the benefits and the risks of release experiments is extremely difficult, since the behaviour of the upper atmosphere is not well understood, and since comparisons of benefits to one discipline and risk to another is inevitably subjective. Nevertheless, consideration should be given to the establishment, by competent scientific organizations, of limits on the releases of various materials in the space environment.

C. Nuclear explosions

36. In addition to the nuclear explosions at or near ground level, explosions have been conducted in the upper atmosphere at altitudes around 400 km. Such experiments were conducted in the late 1950s and early 1960s with the intention of studying their geophysical consequences. The short term effects were almost negligible on the ground, but were large and extensive in the high atmosphere. In contrast to radiation from low altitude explosions, which is absorbed within a short distance by the dense air, particles and X-radiation from high altitude explosions travel over large distances. As a result, the first large high altitude explosion killed, by its radiation, the electronic devices of several satellites which were in orbit at that time. Charged particles produced in a northern hemisphere explosion, after travelling along the force lines of the magnetic field of the earth, produced an artificial aurora over New Zealand only seconds after ignition. Radio wave absorption in the ionosphere was increased a few minutes later. Synchrotron radiation from 2MeV electrons produced by the explosion was detected by radio astronomy observations at low latitude. Charged particles produced in the explosion largely increased the population of the natural radiation belt. Following another (1 kiloton) explosion at low latitude, an artificial radiation belt was created which lasted many years; similar explosions at high latitude produced belts that decayed rather rapidly.

D. Ion beams

37. In recent years, for scientific purposes, electrons and ions have been ejected into the upper atmosphere in a controlled manner by activating suitable sources

aboard space vehicles. Until now the importance of such "charged releases" or "beams" has been at or below the levels of naturally occurring processes. This situation may change as man's presence in space grows, and as powerful ion engines are increasingly used in the future for propulsion, as is already intended in different projects now under discussion. Such engines will be required, for example, to propel large satellites from a lower-altitude parking and construction orbit into a geostationary orbit. In case of such activities the effects of ion engines will no longer be minimal.

38. The most powerful electron beams that have so far been fired into the ionosphere produced an electric current of below 1 A supported by electrons of about 20 keV energy. The beam provoked an artificial aurora of very weak intensity, which could only be detected with sensitive instrumentation, and a variety of waves in the plasma, with weak intensities comparable to those of natural emissions. Radar reflections could be obtained from the beam, and bursts of radio noise were observed. The electron beams often provoked the creation of instabilities in the plasma and a hot plasma halo was formed around the rocket.

39. Injection of ion beams (caesium and xenon ions were used) also produced plasma waves and instabilities. These were studied in view of the natural occurrence of such phenomena and the search for a scientific explanation. Induced emission at the fundamental resonance frequency (of the ions in the local magnetic field) was observed with many harmonic frequencies up to twenty times the fundamental one. In other experiments it was confirmed that ions released in the upper ionosphere did not appear as contamination at much higher altitude in the magnetosphere.

40. Ion engines for propulsion, called ion thrusters, emit beams of particularly heavy ions. The currents now being used cause no harm, but more powerful engines are being planned. A proposed ion engine for transferring heavy structures from a lower into a geostationary orbit would deposit 1 million kg of argon into the magnetosphere, so creating an ion population about equal to the natural ion content of the magnetosphere, but of much larger energy. Such techniques could produce strong and long-lasting distortions of the outermost environment of the earth. Many questions are still open to discussion in this context, including the reaction processes involved, and the time delays for the natural recovery after such operations. Preliminary experimentation with smaller ion thrusters in the magnetosphere could provide some answers to these questions.

E. Electromagnetic waves

41. Electromagnetic waves are now also experimentally produced in space, for example for feeding energy into natural or artificial particle populations. Such experiments are part of a new discipline in space research which uses the orbital environment as a laboratory providing conditions that cannot be achieved in a laboratory at ground level. Controlled experiments of this kind are normally sporadic and therefore of no serious consequence because with currently used power levels, recovery is quick in the ionosphere and even in the magnetosphere. However, emissions due to man's day-to-day activities may not be negligible in the outermost

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environment of earth. At present, these stem mainly from ground-based installations, viz. from powerful radio transmitters, including radars and, at extremely low frequencies, from the terrestrial power lines which emit harmonics of their 50 and 60 Hz fundamental frequencies. The effects of such emissions have clearly been demonstrated, but controversy still exists on their magnitude.

42. Suitable chosen waves in the HF range may provoke considerable heating of the electron and ion populations in the ionosphere. Installations at ground level must have extremely high power (of the order of megawatts (MW)) so as to produce strong fields at 100 km distance in the ionosphere. Similar experiments might be conducted in the future from larger spacecraft, but of course with much smaller transmitter power. The power density in the ionosphere, actually attained with the MW transmissions from ground level is comparable with that reached at 1 km distance from a 20 kW transmitter. It has been shown that such rather modest energy fluxes are sufficient to modify conditions in the ionospheric medium and to create irregular structures ("cavities") with sizes of some metres. These have been shown to change considerably the usual conditions of radio wave propagation in the ionosphere by scattering wave energy in unexpected directions. While in certain regions of earth such phenomena occur naturally, they are rather rare at temperate latitudes.

43. Wave-particle-interaction is a subject of some interest in space research and astrophysics, but also for certain electrical technologies. Only in space can such phenomena be studied, since very long radio waves (in the VLF range) must be used. If a wave of suitable frequency is emitted in the magnetosphere, it can gain energy from the electrons which are "trapped" in the radiation belt and so be amplified. At the same time the electrons are precipitated down into the ionosphere. It is a matter of some controversy how important human activity is, even at its present level, in provoking such phenomena which were formerly considered as being due to natural causes. In short, it seems that radiations from ground level, in the VLF and other ranges, can affect the natural charged particle population in the magnetosphere to a certain extent.

44. It seems probable that larger effects might be produced if, in the future, greater energy densities were generated in the magnetosphere through the use of lower-power transmitters aboard space vehicles.

45. Additional disturbances are introduced by powerful emitters of VHF radio waves. On board emitters of HF and VHF waves generate electric and magnetic fields at large distances from the satellite. Usually, the aerials of these emitters are strictly directional and cause very large electromagnetic fields at their apertures. In the beam direction of the radiation pattern of such an antenna, the electric and magnetic effect of a satellite reaches the earth. In the most extreme case of an SPS so far designed, the enormous energy flux may significantly perturb the ionosphere and, when reaching the earth's surface, may even be harmful to the biosphere.

46. The energy fluxes in the side lobes of a relatively poorly directional onboard antenna attain significant values, and increase the electromagnetic effect of the

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satellite to a distance of about 1,000 km. Particularly dramatic is the case of an SPS, in that the desired directional properties of the VHF antennas cannot be guaranteed under such great powers; the energy within the side lobes would be sufficient to disturb communications with other satellites and also to affect people and systems on the ground. Especially drastic would be the case were oscillations of a stabilized SPS to occur. This effect would lead to a sharp increase of the size of the disturbed area around the satellite and could alter the operation of other geosynchronous spacecraft, communications systems in particular. For an SPS with 1,000 MW, this disturbed region could extend over several thousand km. For a detailed discussion of the area subject to electromagnetic disturbances by a satellite, see annex II.

F. Material sciences in space

47. This new discipline uses the (near earth) space environment either as a laboratory in which gravity is extremely low (microgravity), or as an extremely powerful vacuum pumping system. Experiments made so far have used microgravity for investigating material processes (e.g. melting and recrystallization) in the absence of disturbances normally induced by gravity in terrestrial laboratories (e.g. gravity excited turbulence). The experimental structures themselves, if at all exposed to space, may modify the immediate environment of the vehicle by outgassing, but the masses involved will remain small (not more than 1 g per experiment). Moreover, the types of gases in question will be those occurring naturally in the high atmosphere, including, however, water vapour and carbon dioxide. Larger releases may take place from cooling systems, and for this reason designers should use only non-aggressive species such as helium. For example, in the first SPACELAB mission, a release of 150 g of helium is envisaged.

48. The use of a windshield outside the vehicle for creating a vacuum of extremely high quality is now being considered. Here too, care should be taken tc avoid pumping vapours or gases that are aggressive to the natural upper atmosphere into the space environment.

III. POSSIBLE DIRECT EFFECTS ON HUMAN LIFE

A. Debris from spacecraft

49. During the final re-entry of a spacecraft into the earth's atmosphere, it gradually breaks up leaving a trail of debris scattered over a fairly long, but narrow, track. Two recent events of this kind have received attention: the re-entry of SKYLAB over Western Australia and the fall of Cosmos-954 in Northwest Canada. In both cases, the break-up took place over uninhabited or very sparsely populated regions, and there were no casualties. Nevertheless, they demonstrate the risk and the need to take whatever steps are possible to reduce it.

50. The chance that a particular individual will be killed by a falling spacecraft is probably not greater than of being hit by a crashing aircraft. However, in view

of the population of the world as a whole, the risk that someone may be hit is not completely negligible.

51. Several methods of minimizing the risk are available, and the most important is probably that of controlled re-entry. This implies that the spacecraft remains under control from the ground until its final orbit. Then, at an appropriate point in this orbit, a rocket motor is activated which slows down the spacecraft and allows it to fall into a predetermined area over the sea or an unpopulated land region. Other possibilities are the transfer of the spacecraft into a higher level orbit, in which its lifetime will be greatly extended, or to arrange for its complete destruction before final re-entry. These methods are discussed in more detail in Chapter IV.

52. Particular problems arise in the case of satellites carrying nuclear power systems due to the danger of radio-active material being introduced into the environment. The greatest risk arises when radio-active debris reaches the surface, but the introduction of radio-activity into the upper atmosphere through the disintegration and vaporization of the spacecraft may also have undesirable effects. Normally, however, the vaporization of a nuclear power system on re-entry would result in exposure to radio-activity at the surface well below the natural background and within the limits set by the International Commission on Radiological Protection (ICRP).

53. For low levels of electrical power (up to 475 watts electrical power has been generated) radio-isotope thermo-electric generators have been used on satellites such as Lunokhod (USSR) and Voyager (United States) where other power systems could not meet the mission requirements. Radio-isotopes that have been used include plutonium 238 (half-life 87.7 years) and Polonium-210 (half-life 138 days). Normally these materials are enclosed in containers designed to survive re-entry and reach the surface intact. Radio-isotope power sources are also used as heat sources, and small quantities of radio-isotopes are used in some scientific instruments.

54. Higher levels of electric power can be generated by nuclear reactors using radio-active materials such as Uranium-235 as fuel and generating a variety of radio-active products, most with rather short half-lives. Such systems have been used on the Snapshot (United States) and Cosmos-954 (USSR) satellites. Since reactor power systems tend to be larger and more complex than radio-isotope power systems, it is much more difficult to design the system to survive re-entry. In cases of emergency re-entry therefore, the reactors are designed to disintegrate and vaporize in the upper atmosphere.

55. Satellites carrying nuclear power systems are generally designed either to operate in high altitude (long lifetime) orbits or, in the case of missions requiring lower orbits, to be moved to high orbits at the end of the working mission. Lifetimes of satellites cannot now be accurately predicted, but at an initial altitude above 800 km, the lifetime should be at least several hundred years, and above 1000 km, the lifetime should be greater than 1000 years. In 400 years, the fission product activity of a Uranium-235 reactor should be about 1/1000 of the activity one year after reactor shut-down.

56. The risks from nuclear power systems arise primarily from the possibility of failure of the satellite to reach high orbit combined with the failure of the mechanism designed to ensure the survival of the fuel containers in the case of radio-isotope systems, or ensure the complete vaporization of the radio-active material in the case of reactor systems. A few satellites carrying nuclear power systems have failed on launch or have re-entered the atmosphere prematurely:

(a) Transit-5-BN-3, launched on 21 April 1964, failed to reach orbit and re-entered the atmosphere at an altitude of 121 km. The radio-isotope system disintegrated and vaporized in the upper atmosphere as designed.

(b) NIMBUS-B-1, launched 18 May 1968, failed on launch and fell into the ocean. The radio-isotope system was recovered intact.

(c) Apollo 13, launched 11 April 1970, failed in circumlunar flight. The radio-isotope system re-entered the atmosphere and was lost intact in the deep ocean.

(d) Cosmos 954, launched 18 September 1974, failed in low orbit and re-entered the atmosphere on 24 January 1978. The reactor system disintegrated but did not completely vaporize, and some radio-active material reached the ground.

57. It is clear that great efforts have been made to protect the terrestrial environment from radio-active material from nuclear power systems, but it is equally clear that it is not possible to provide absolute guarantees against failure of the protection systems. It should be noted that the United Nations Committee on the Peaceful Uses of Outer Space has established a Working Group on the Use of Nuclear Power Sources in Outer Space to consider the technical aspects and safety measures relating to the use of nuclear power systems.

B. Balloons

58. Balloons are used for making measurements in the atmosphere at heights that are not accessible to satellites. Since such balloons must ultimately return to the ground, clearly some care is essential on the part of the users. In order to avoid the risk of collisions with aircraft, recommendations have been issued by the International Civil Aviation Organisation. At present, all short-term balloon flights are carried out in conformity with these recommendations. At national level, local operational relationships are established between the balloon launching teams and the air traffic organizations.

59. The return to the ground of heavy payloads is controlled by a parachute, which reduces the rate of fall to a safe level. As for the large balloons themselves, they can be disintegrated into very low density shreds by means of tearing devices operated after the release of the load.

C. Solar power satellites

60. Proposals for SPS envisage the construction in space of very large structures for collecting solar power and transmitting it to the ground by microwave beams.

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The satellites will use highly directional transmitting antennas in space for the transfer of energy to the ground at a radio frequency of 2.45 GHz. The very intense beam will be directed into special antennas on the ground, but there will also be some stray radiation, at a much lower level, to which the general population and the ecology will be exposed. Workers at the ground and space antenna sites will, of course, be exposed to somewhat higher levels of radiation.

61. Very little evidence is available on the danger to health and to the ecology of long-term exposure to weak microwave radiation. Some short-term experiments on animals and plants exposed to high intensity radiation have been made, but the results are often contradictory and, in any case, the extrapolation of the results to long-term low-level radiations is open to doubt. There is a need for an extensive investigation of these risks in order to determine whether the use of microwave beams for the transmission is feasible.

62. Mention should also be made of several other risks relating to the SPS. Because of the large quantities of gallium arsenide used in the solar cells, the workers handling the antenna components will be subject to risk of contamination. Those working on the antenna in orbit will also be exposed to space radiation, the effects of long periods of weightlessness, etc. Current experience is providing some information on the risks involved and on the protective measures that must be developed.

63. Since the satellites require very large areas of solar panels - on the order of 50 sq km, a large number of powerful rockets will be required to transport the materials, first into low orbit for assembly, then into the geostationary orbit for operation. The possible risks during launch are discussed in Chapter II.

D. Laser beams

64. The very narrow but intense beams emitted by lasers have many applications on the ground and in space. However, exposure to an intense laser beam can cause burns and skin damage and precautions must be taken to avoid such accidents. There is a possibility that a laser beam emitted either from the ground or from a spacecraft may be accidentally directed towards an aircraft, but it should be pointed out that no accident of this kind has occurred during the past 15 years when lasers have been used in ranging satellites. Although a laser beam in a spacecraft could illuminate the earth's surface, the distance travelled by the beam would be so great that no hazard would be involved.

E. Exobiology

65. It has been suggested that there are possible biological risks associated with space activities though there is no evidence that any danger really exists. Three possible risks have been suggested:

(a) The risk that terrestrial micro-organisms carried by space vehicles may contaminate the surface of other planets;

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(b) The risk that extraterrestrial micro-organisms carried by space vehicles returning with samples from other planets may contaminate the earth;

(c) The risk that terrestrial micro-organisms that have been exposed to the space environment may build up mutations which could be dangerous for man.

66. As far as the first of these risks is concerned, only the surface of Mars need be considered, since the surfaces of the other planets are so hostile to life that they would be totally unsuitable to the development of terrestrial organisms. Even on Mars, although the surface temperature and the atmosphere would not preclude the continued existence of the more resistant terrestrial micro-organisms, their development would be highly unlikely because of the lack of free water, the scarcity of soil nutrients and organic matter, and the intense solar ultra-violet radiation. In any case, space probes which are intended to land on planets are sterilized and, taking everything into account, it is believed that the risk of contamination of the planets is negligibly small.

67. Those who envisage the second of the biological hazards suggest that the introduction of micro-organisms from, say, Mars could be the starting point of an epidemic of some unknown Martian disease. However, this suggestion presupposes a high degree of functional overlap and chemical compatibility between terrestrial and Martian life forms. Even if the surface of Mars were more like that of the earth than it appears to be, the separate biochemistries of the two independently evolved systems imply that it is extremely unlikely that a hypothetic Martian parasite could thrive and develop in a terrestrial host. It should be added that no evidence has been found for the existence of plant or animal forms on Mars which might be considered as representing a potential danger to terrestrial life.

68. The additional point has been made that terrestrial micro-organisms that have been isolated for very long periods in high mountains, caves or polar regions, and which share a common evolutionary heritage with other inhabitants of the biosphere, would be likely to present a far greater danger than samples imported from Mars.

69. It is probable that terrestrial organisms that have been exposed to space conditions will build up mutations. However, for many years genetic and radiation biological research has been in progress and, as yet there has not been any reported case of the discovery of a mutant capable of infecting, or disrupting biogeochemical cycling, or of otherwise destroying parts of the biosphere.

IV. PHYSICAL CONGESTION OF THE ORBITAL ENVIRONMENT

A. Number and distribution of objects

70. With the present population of satellites, problems of interference between satellites have been largely restricted to problems of radio-frequency interference, a subject that is handled within the International Telecommunication Union (ITU). Physical interference between satellites has not been a problem but as satellites become larger and more numerous, the probability of collision and shadowing may become a problem.

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71. Artificial objects in outer space can be divided into two groups, those that can be observed by radar, telescope or other tracking device, and those that cannot. Current systems are capable of tracking objects less than a square meter in cross section in low orbit. All launchings are announced through the United Nations and through COSPAR which also assigns international designations to trackable objects. Currently there are some 4600 trackable artificial objects in outer space.

72. As figure 4 shows, yearly numbers of launchings, after a sharp rise between 1957 and 1965, have been, with some fluctuations, almost constant with an average of 116 launchings per year. In a single launching, one or more satellites can be put into orbit while a certain number of non-functional objects, such as exhausted rocket stages, nuts and bolts, either fall back to the ground or follow the payload in approximately the same orbit. Only fairly large non-functional objects are tracked. Figure 5 shows the total number of trackable objects from 1974 to the spring of 1980. The increase between 1974 and 1978 indicates that the number of new objects exceeded the number of objects which decayed in the atmosphere. From 1978 to 1980, however, the total number of trackable objects decreased slightly. Since the launching activity remained about the same in that period, either the technology of launching improved by reducing numbers of non-functional objects, or the maximum of solar activity in 1979-1980 which caused higher average densities of the atmosphere and thus shortened the lifetimes of space objects, speeded up the cleaning up of near outer space.

73. The debris of nuts and bolts and small fragments which escape tracking and detection move at a speed exceeding that of projectiles. If they collide with a satellite they may damage it seriously. Two recent malfunctions of satellites have, indeed, been ascribed to possible collisions with space debris. The numbers, sizes and orbits of untrackable debris can only be estimated. It seems that about twice as many untrackable objects are generated than trackable objects. Since the former are smaller, they decay faster and thus the actual number of untrackable objects can be estimated at about 5,000, i.e. not much different from the number of trackable objects.

74. Even more difficult than estimating the present situation is its projection into the future. Some scientists maintain that new debris associated with the launch or break-up of a payload or a rocket are being generated faster than they decay in the atmosphere. Once the collisional break-up begins - and it may have already begun - the number of pieces of debris would increase exponentially with time. It may quickly exceed the natural meteoroid flux and it may lead to the formation of a debris belt around the earth where only heavily protected spacecraft would survive. Other scientists point out the role of solar activity which, at its maximum, significantly contributes to the clean-up of near outer space. This mechanism is active for two to three years near the maximum of the 11-year cycle of solar activity.

75. The question of untrackable debris deserves further study extending over several cycles of solar activity, because the numbers and sizes of debris may be very important in considering the safety of future space missions.

76. It may be useful to compare numbers of artificial objects with the flux of meteors entering the earth's atmosphere. The estimated annual numbers of various sizes are:

1 mm	4×10^{10}	per year
1 cm	3×10^{7}	per year
10 cm	4×10^{3}	per year
1 m	40	per year

77. The shape and the orientation of a satellite's orbit in space are more or less variable. On the other hand, the orbital inclination is relatively constant, subject only to small and slow changes caused by the rotation of the atmosphere and by gravitational perturbations. Accordingly, the distribution or orbital inclinations is influenced only by new launches, since even an explosion or collision would leave most of the fragments in the proximity of the orbital plane. Figure 6 shows the distribution of the inclinations of orbital planes and numbers of objects orbiting in those planes.

78. The maximum near 0° latitude belongs to equatorial orbits such as the geostationary orbit. The maxima around 30° and 60° reflect, at least partly, the location of launching sites. The highly eccentric orbits of some communication satellites favour inclinations above 60°. Satellites in orbits at about 80° overfly all inhabited regions of the world, while strictly polar orbits, at an inclination of 90°, do not seem to be that much in demand. Sun-synchronous orbits have inclinations between 95° and 105°. There are very few satellites in orbits at inclinations higher than that.

79. Spatial density is defined as the number of objects found on the average, in a unit of volume. Here we use, as a reference volume, a cube with sides measuring 1,000 km. Due to the rapid motion of space objects, this spatial density exhibits large and rapid variations. The actual number of objects may at times differ by up to 50 per cent from the average value. The spatial density depends on orbital properties since satellites spend more time near their apogees than near their perigees. Moreover, all orbits cross the equatorial plane, whereas at a given geographical latitude only those objects which have orbital inclinations at least equal to that latitude can appear.

80. The density (see figures 7 and 8) varies with increasing altitude above the earth. From 100 km altitude, below which no space objects survive for any appreciable length of time, the spatial density increases with altitude. In the most densely populated region, between 500 and 1,000 km, almost 100 objects are found per reference cube, 60 out of that number being trackable objects, the rest untrackable debris. There are several peaks and valleys of density in that region. Another peak of relatively high density occurs at 1,450 km altitude. The density falls to three objects at 2,000 km and to one object per reference cube at 3,000 km. Two small peaks appear at about 3,700 km and at the altitude of the geostationary orbit, 35,800 km. As can be seen from figure 7, the density peaks are highest in the equatorial plane, becoming slightly lower at higher geographical latitudes.

81. The geostationary orbit is a special case in that the spatial density is rather high and growing, and the relative positions of satellites are fixed. Large satellites can therefore cause prolonged shadowing of their neighbours. Most satellites and space stations use as a primary energy source solar radiation backed up by batteries. Should solar radiation be cut off for a longer period than that for which the batteries have been designed, some functions might be interrupted. The shadow of a space object can be more than 100 times as long as its dimension. A 20 km solar power station would throw a shadow extending over 2,000 km which, at the geostationary orbit, corresponds to almost 3° in longitude. A small communication satellite designed to work in the close neighbourhood of a solar power station should have either the capability of steering out of the shadow or an alternate source of energy.

B. Collisions

82. Three parameters determine collision probability: the spatial density of objects, the cross sections of the objects and their relative velocity. The spatial density is the most important factor, because the collision probability increases with the square of the density. Thus, the danger of collisions is greatest in most densely populated regions of outer space.

83. The satellite cross-section is not very important at present since most satellites are rather small bodies which present a small target area to the rapidly flying debris. The situation will be entirely different for large space stations with dimensions of an entirely different order of magnitude. At the time such stations are planned, the question of collision probabilities will have to be discussed in detail.

84. The velocity of a space object is given by laws of orbital mechanics, unless the body is being propelled by engines. The velocity is largest at the satellite's perigee; it is constant for satellites in circular orbits. An investigation of a representative sample of space objects yielded an average velocity of 7 km/s, and a maximum of 14 km/s. An impact at that speed destroys the smaller of the two colliding bodies and ejects more than 100 times its mass from the larger body.

85. The results of a computation of collision probabilities, or collision frequencies, are shown in figure 8. The left-hand scale gives the number of years within which a collision is to be expected at an altitude shown on the bottom scale. The highest probability of one collision in 20 years occurs in the most densely populated regions between 500 and 1,000 km altitude. Only one collision in a few hundred years is likely to occur at 1,200-1,300 km and the expectation is still lower above some 1,600 km.

86. The above data are valid for the present population of space objects. Should space activity markedly increase in the future or should the number of pieces of debris build up during the coming minimum of solar activity, or should the next solar maximum be lower than the maximum of 1979-1980, such collision probabilities would have to be revised upwards.

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87. The probability of collisions was justifiably overlooked in the first decades of space activities. It may, however, become an important factor in the future if more and larger satellites and stations are launched into outer space. Since preventing all collisions is impossible, technical means might at least be used to reduce the probabilities of collisions. Such measures would be expensive; however, the sooner they are taken, the smaller might be the real cost. The most obvious way of reducing the probability of collision is to reduce the number of pieces of debris produced during the launching phase and during the lifetime of a satellite. Other options for removing satellites which are no longer active from frequently used regions of outer space are available and should also be considered.

C. Removal of inactive satellites

1. Natural forces

88. The density of the upper atmosphere decreases exponentially with height above the earth's surface, and is only about 10 gram/cubic kilometre at a height near 350 km. However, a satellite moves at a speed of nearly 8 km per second, and its collisions with the air molecules are frequent enough to create a considerable drag force. If the orbit is non-circular, the air drag is much greater at perigee than at apogee. The satellite is thus retarded at perigee, and does not fly out as far as expected at apogee. Hence, the orbit contracts with a tendency to become circular, as shown in figure 9. If the orbit is initially circular, air drag acts continuously along the orbit, thus reducing the height of the orbit gradually.

89. For both circular and elliptic orbits, the drag rapidly increases as perigee height decreases. At perigee heights of about 100 km the satellite can no longer remain in orbit and begins its final plunge into the lower atmosphere. It should be noted that, although air drag retards the satellite at perigee, the over-all effect of air drag is to make the satellite move faster. Its orbital period decreases as its lifetime progresses and final decay usually occurs when the orbital period has decreased to about 87 minutes. A more complete discussion of the stability of satellite orbits is given in annex I.

90. The braking force due to air drag depends on the density of the upper atmosphere, which varies widely and irregularly. Predictions of decay depend in particular on future variations of solar activity which are at present unpredictable in detail. Of 4,600 objects in orbit being tracked, about 10 per week are slowed down to the point at which they re-enter the atmosphere. The majority of these are small fragments which burn up in the lower atmosphere, but an important proportion (about two per week) are large objects with a mass of more than a ton. Fragments of up to 10 kg in weight may reach the earth's surface when these large space objects decay.

91. The procedure for predicting satellite decay is first to assume that the air density remains constant during the rest of the life of the satellite, and to calculate, either from theory or by numerical integration, the date at which the perigee will descend below 100 km. The observed current rate of decay of orbital period is used as a measure of the air drag. Then, adjustments are made to this basic calculation to take into account variations in the air density. In the

absence of such variations in air density the lifetime could be accurately predicted if the satellite retained a constant cross-sectional area. But, in practice, the air density varies, and lifetime estimates having an accuracy of ± 10 per cent are about the best that can consistently be achieved.

92. If the perigee height is greater than about 500 km, the orbital lifetime is usually 20 years or more, but most satellites have perigee heights between 200 and 500 km, and for these the orbital lifetime may be only a few days, or a few months, or a few years, depending on the exact orbit and the area/mass ratio of the satellite.

93. In predicting orbital lifetimes, the most uncertain factor is the great variation in air density at a height of a few hundred km when the solar activity varies from sunspot maximum (1969 and 1979) to sunspot minimum (1976). At a height of 500 km the density is about 10 times greater at sunspot maximum than at sunspot minimum. Therefore, a satellite in a circular orbit at a height of 500 km might have a lifetime of about five years if launched shortly before solar minimum, but a lifetime of six months if launched at solar maximum. There is also a large variation in density between day and night, the density being higher by day than by night by a factor of up to about five at a height of 500 km. This variation must also be allowed for in predicting orbital lifetimes.

94. Unfortunately, at present, the progress of the solar cycle cannot be predicted accurately enough for good predictions of satellite decay. Solar activity also shows vigorous and unpredictable variations from day to day. There is normally a fairly steady outflow of plasma from the sun, termed the solar wind, but this is disrupted by shock waves when a solar disturbance occurs. When the shock waves reach the earth, the upper atmosphere responds strongly. At heights near 600 km, the density may increase by a factor of up to eight following a solar storm, and even at heights as low as 180 km the density may be doubled within a few hours. Thus predictions that a particular satellite will decay in a week or 10 days can be seriously affected if an unpredicted solar disturbance occurs in the meantime.

95. The unpredictability of solar activity is the main difficulty in forecasting satellite lifetimes of several years or even of a few days. For lifetimes of intermediate length, i.e. between one month and one year, another partially unpredictable variation becomes more important; this is the semi-annual variation in atmospheric density which exhibits maxima in April and early November, and minima in January and July. Lifetime predictions can be in error by up to 30 per cent if no allowance is made for this semi-annual variation. Unfortunately, the semi-annual variation itself changes appreciably from year to year. The future variation of the semi-annual effect is not predictable with the present state of knowledge of upper atmosphere physics.

96. The prediction of satellite lifetimes is therefore likely to remain an inaccurate procedure. For lifetimes of between 1 and 20 years, the long-term forecasts of solar activity during a sunspot cycle are inadequate. For lifetimes bween one month and one year, solar activity is still a major source of uncertainty (except near sunspot minimum), and so is the future course of the semi-annual variation in atmosphere density. For lifetimes of less than one month, the

day-to-day variations in density resulting from short-term solar disturbances are the major source of error. To achieve a lifetime prediction with an accuracy of ± 10 per cent, in the light of these problems, calls for considerable skill and experience. Account has to be taken of interaction of many factors, e.g., the future variations of perigee height due to both geometrical and dynamic factors, and the synchronization of such variations with changing solar activity.

97. Although most satellites decay because their orbits steadily contract under the action of air drag, a small but important proportion of satellites have their orbital lifetimes reduced because the perigee is forced down into the lower atmosphere by luni-solar perturbations. Since the luni-solar perturbations are accurately predictable and drag may not have an appreciable effect until the last few revolutions, the decay of such orbits is, in principle, quite accurately predictable. Unfortunately, however, such satellites are usually very difficult to track, because they move out to very great distances from the earth. Consequently, their orbits are not well-determined, and the accuracy of the predictions is usually limited by the accuracy of the orbital parameters available.

2. Orbital transfers

98. In some cases, it may become desirable to alter artificially the natural course of events. In low orbits, since the decay and, especially, the site of impact on the earth's surface are not predictable with sufficient accuracy, a controlled landing or a controlled decay in the atmosphere might be preferable. In some cases, the natural decay might have to be delayed by moving the satellite into a higher orbit with a longer lifetime.

99. A controlled landing or decay of a satellite in a high orbit might require prohibitive amounts of propellant. Such satellites could, however, be removed into disposal orbits, beyond the paths of active satellites.

100. In order to effect the removal of an active satellite from its orbit, some of its systems must be operational at that time, in particular the communication systems and the systems for satellite orientation and stabilization. The former are required to provide necessary commands and the latter are necessary for assuring the correct direction to the applied force. These conditions are satisfied in only a few satellites. Soviet orbital stations of the Salyut type and cargo-spacecraft of the Progress type are pushed into the earth's lower atmosphere before their active lifetimes expire. Similarly, INTELSAT communication satellites are removed from their geostationary positions when a new satellite is launched.

101. The overwhelming majority of objects presently in orbit are inactive satellites (or debris) which cannot be removed from their orbits without some external assistance. Such satellites might be caught by the remote manipulator arm of the Space Shuttle, or some manoeuvring rocket-powered unit could be attached to them in order to provide them with a manoeuvring capability. However, better removal methods (in terms of energy conservation) can be found in making use of natural forces.

102. In principle, natural forces can also be used to effect rapid changes of the orbit. For example, a close encounter of a satellite with a natural celestial body might change its orbit profoundly. Or, the effective area-to-mass ratio of a satellite can be changed by the deployment of large "wings". This would increase the influence of non-gravitational forces (air drag, radiation pressure) which, in turn, might cause faster decay. These methods, however, have not found practical application as yet.

103. In order to change the orbit of a satellite, it is necessary to change its kinetic energy, which is proportional to the square of its velocity. The theory of orbital transfers between circular orbits was elaborated as early as 1925 by W. Hohmann. He proved that the trajectory that connects two circular orbits in such a manner that it is tangential to both requires minimum velocity change and therefore minimum consumption of propellant. During such a transfer, the satellite travels exactly half the elliptical transfer orbit, called the Hohmann orbit. Transfer orbits, which are longer or shorter than Hohmann orbits, require larger velocity impulses. The orbital transfer involving two elliptical orbits can be treated similarly. Generally, it is preferable to perform a Hohmann transfer between the perigee of the initial orbit and the apogee of the final orbit. If the orientation of the planes of the two elliptical orbits is different, more than two impulses are necessary to accomplish the transfer.

104. The fundamental equation of rocket propulsion which is applicable to classical chemical rocket systems expresses the velocity of the vehicle in terms of specific impulse, which depends on the effective exhaust velocity of gases from the motor and the ratio of initial and final masses of the vehicle. Therefore, for a required change of velocity, using a specific propellant, one can compute the necessary amount of the propellant. As an example, for a typical geostationary satellite of the INTELSAT IV type (mass 700 kg), 34 kg of hydrazine is needed to achieve a velocity change of 100 m/s.

105. Large velocity changes would demand amounts of propellant which would greatly increase the total mass of the satellite. Therefore, a careful analysis is necessary in order to minimize such manoeuvres.

3. Planned decay

106. The decay of a satellite in the atmosphere can be induced by pushing it into an elliptical Hohmann transfer orbit in which the satellite travels half of a revolution reaching the perigee at 100 km or preferably lower. The decelerating kick is applied in a direction opposite to the orbital velocity (see figure 10), and its magnitude depends on the radius of the initial orbit. For altitudes up to the geostationary orbit, the higher the orbit, the greater the necessary retro-kick (see figure 11). If the satellite is in an elliptical orbit, the optimal retro-kick is applied at apogee and its magnitude is always smaller than for a circular orbit at the same height. The lower the perigee, the smaller is the necessary retro-kick. Obviously, if the perigee is already at 100 km, no impulse is required.

107. However, the use of a Hohmann orbit with a perigee at exactly 100 km is not a very safe method for removing a satellite from its orbit, because the satellite would travel horizontally at the perigee of the Hohmann orbit. It could happen that atmospheric drag would not be sufficient to "catch" the satellite. This situation is similar to the ballistic re-entry of spacecraft with high velocities (e.g. from a lunar mission), where the spacecraft "bounces" off the top of the atmosphere, i.e. "atmospheric skip" occurs if the angle to the local horizon is less than 3°. Therefore, when planning re-entry, it is advantageous to increase the retro-kick for low orbits by a few per cent and to increase the re-entry angle to ensure atmospheric capture and a speedy decay.

108. Once in the atmosphere, the descending body moves according to the laws of aerodynamics. Its final fate depends on many factors of which the most important are the entry velocity, shape and area-to-mass ratio of the body, and the thermal and mechanical characteristics of its structure. Usually the object is destroyed at a certain altitude, but a few of the resulting debris are capable of reaching the earth's surface. Up to the end of 1979, from the 6,733 objects which had already decayed, fragments surviving re-entry had been recovered on land in only 16 cases.

109. The conclusion could be drawn that, for low orbits (figure 12), pushing the satellite into the earth's atmosphere is an effective means of removal. An application of the minimum necessary retro-kick results in long trajectories and in small angles of atmospheric entry. Larger retro-kicks increase the re-entry angles and for some values (which are used for re-entry of manned spacecraft) both thermal loading and mechanical overloading are relatively small, leading to a high probability for the survival of fragments which can consequently hit the earth's surface. For even greater velocities (and re-entry angles), mechanical overloading increases and destroys the object.

110. By timing the retro-firing carefully, a decay over uninhabited areas or over an ocean can be achieved. In such cases, resulting fragments have little chance of causing damage even if they reach the earth's surface.

4. Ejection from earth orbit

111. The gravitational acceleration produced by a celestial body decreases with the square of the distance between that body and the satellite, according to Newton's law of gravitation. Consequently, the gravitational influence of a celestial body is important only up to a limited distance, where the gravity of some other body becomes stronger. The so-called "sphere of influence" of the earth has a radius of approximately 1 million km. At greater distances, the sun's gravity prevails.

112. Should the apogee of an orbit lie beyond 1 million km, the satellite would travel towards the apogee but would not return back to the earth. Such a satellite would leave the sphere of influence of the earth on an escaping trajectory. The difference between the velocity of escape and the circular velocity for various heights above the earth's surface is shown in figures 11 and 12 and labelled "out of

earth's influence". In order to reach the escape velocity, a velocity kick is to be applied in the direction of the orbital motion of the satellite. For elliptical orbits, it is most economical to change the velocity at perigee.

113. What happens to the body after it leaves the earth's gravitational influence depends upon the residual velocity after escape. If this velocity is directed contrary to the earth's revolution around the sun, the body will orbit around the sun inside the earth's orbit and touch the earth's orbit at the point of escape. If the residual velocity is directed along the earth's orbital velocity, the elliptical orbit of the body around the sun is outside the earth's orbit and touches it again at the point of escape. The probability of repeated entry into the earth's sphere of influence is very low, and therefore such orbits have also been considered for the disposal of nuclear waste in space.

114. In order to ensure that the removed body does not reappear within the earth's sphere of influence, it should either be placed in a disposal orbit around the sun which does not cross or touch the earth's orbit, or be pushed out of the solar system completely. To change the 200 km high orbit around the earth into an orbit escaping the solar system requires a velocity impulse of almost 9 km/s. However, pushing the body directly into the sun demands an even greater impulse, a velocity change of 24 km/s. The velocity changes ΔV needed for a simple escape into a solar orbit are much smaller, and are given in figure 11.

5. Disposal orbits

115. Still another method of removing a satellite from its initial orbit is to place it in a disposal orbit. By "disposal orbit" is meant an orbit which is generally higher than the original orbit and located at heights used by no (or only a few) active satellites.

116. For transfer from an initial circular orbit into a circular disposal orbit at a higher altitude, two velocity impulses are necessary. The first impulse changes the initial orbit into a Hohmann transfer, and the second impulse, half an orbit later, changes the Hohmann transfer into the final circular disposal orbit. Both impulses have to be parallel to the orbital velocity, increasing it by the necessary amounts. The first impulse is always larger than the second one since, in the former case, the satellite is nearer the earth's centre of gravity. The change in velocity, ΔV, necessary for increasing the height of a given circular orbit by an increment, Δh, is shown in figure 13. It can be seen that at greater heights even a small velocity kick could cause a significant orbital change (because the gravitational field of the earth is weaker there).

6. Summary

117. The results of this section are summed up in figure 12 which provides a comparison of the three methods for removing satellites from their orbits and shows which of the three methods would be most efficient and economical at a particular altitude.

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(a) For low orbits of a few hundred kilometres above the ground, dumping the satellite into the atmosphere is the most efficient method. The necessary velocity kick requires an amount of propellant that is only a few per cent of the total initial mass of the satellite. Even at a relatively high orbit of 1,500 km, not more than 10 per cent of the initial mass is required.

(b) For medium orbits, between 1,500 and 10,000 km, either atmospheric re-entry or parking in a disposal orbit could be considered. Conveniently selected disposal orbits, not far from the operational orbits, would require only relatively small velocity impulses. Should the disposal orbits be far from the initial orbits, the required amount of propellant might become significant.

(c) For geostationary orbits, at 35,800 km, the disposal orbit appears preferable to other methods. An orbit of about 500 km beyond the geostationary orbit would require an impulse of only 18 m/s, which is well within the limits of the station-keeping systems on board most communication satellites.

(d) For extremely high orbits, above 40,000 km, the most economical method is to push the satellite out of the earth's gravitational sphere of influence altogether.

118. The above methods could be used if future satellites were designed so as to incorporate suitable propulsion systems, or if the propulsion systems used for station-keeping and attitude control contained sufficient propellant.

119. Small satellites and debris already in orbit which are not equipped with propulsion systems cannot be removed from their orbits without a special collecting capability which might become possible in the future. For example, a manned space vehicle would be very convenient for this purpose, since its crew could reach the satellite with a remote manipulator arm and either collect it or attach it to a manoeuvring unit.

120. In the era of frequent manned flights, possibly using reusable space vehicles, the number of inactive satellites might decrease because malfunctioning satellites could be repaired, returned to earth or taken to the dense layers of the atmosphere for decay.

V. IMPACT ON ASTRONOMICAL OBSERVATIONS

A. General considerations

121. For many centuries man has used optical telescopes for making observations of the planets, stars, nebulae and other celestial objects. However, in the past 30 years, as a result of the application of remarkable new techniques, the astronomer now has at his disposal not only the optical window, but also three important new windows through which he can look out into space; these windows are located in the parts of the spectrum which include radio waves, ultra-violet radiation, and X-rays. The radio window can be used either at observatories on the earth's surface, or in high altitude rockets or orbiting spacecraft. On the

other hand, since the terrestrial atmosphere almost completely absorbs ultra-violet and X-radiation, these two windows can be used only by installing the appropriate observing instruments in spacecraft.

122. As a general rule, telescopes are instruments which are designed to collect radiation from weak sources in such a way that it can be recorded photographically, or by some other means, for subsequent examination. Since the radiation to be recorded by an optical telescope is weak, it is obviously necessary to site observatories far from large towns, where the street lighting would be a serious problem because of reflected light from clouds. Similarly a radio telescope must be placed as far as possible from man-made sources of radio waves, and preferably in a site where the local topography helps to shield the telescope from terrestrial transmitters. However, even if all possible precautions have been taken in advance in siting the telescope so as to minimize terrestrial sources of interference, the astronomer can do nothing to prevent artificial satellites from passing across the field of view of his telescope.

123. Satellites reflect sunlight in the same way as the planets in the solar system, and hence a satellite which crosses the field of view of an optical telescope can destroy or distort the information that is being looked for. All satellites include radio transmitters, which are used both directly, in making scientific observations, or indirectly for transmitting down to the ground the observations made in the satellite. The radio emissions from satellites are very strong in comparison with the radio waves emitted by most radio stars or by the clouds of interstellar gas which are found in space. Hence it is clear that the passage of a satellite can be a potential source of interference to a radio telescope.

B. Optical astronomy

124. In order to assess the magnitude of the potential interference caused by satellites to optical astronomy, it is necessary to bear in mind such questions as the total number of satellites at present in orbit, the possible numbers in future, their heights, the type of camera used, etc. For example, it has been calculated that, at the present time, the type of photograph taken by a Schmidt camera (which has a wide field of view) will almost certainly include a trace caused by the passage of an artificial satellite. On the other hand, for spectroscopic observations (using a small field of view) the chance of interference by a satellite is less than 1 per cent. Satellite tracks on photographs of stars can usually be identified visually. However, automatic measuring machines are being increasingly used in order to reduce the manual effort necessary for the analysis of certain types of photograph, and there are difficulties in designing the machines to recognize and eliminate satellite tracks.

125. During astronomical observations which involve making recordings or other measurements over periods of tens of minutes or several hours, the passage of a satellite across the field of view of the observing instrument may not always be serious, provided that it is possible to identify the short-term disturbance caused by the satellite. On the other hand, astronomers are also interested in making

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observations of certain types of transient phenomena which take place within a period of a few minutes. In these circumstances, it is possible that the passage of a satellite across the field of view of an instrument designed to record short-term phenomena may be misinterpreted as something else.

C. Infra-red astronomy

126. Artificial satellites have a temperature of roughly 300 K, and hence they emit, spontaneously, infra-red radiation which is very strong in comparison with the weak sources being investigated in infra-red astronomical programmes. Even if no strongly radiating satellite passes through the beam of an infra-red telescope, large numbers of satellites will necessarily, in combination, lead to an increase in the level of background radiation with undesirable consequences.

127. The particular case of the proposed SPS must be mentioned because it is estimated that such a large object would be similar, so far as infra-red radiation is concerned, to a full moon. It follows then that the only infra-red observations that could be made would be those where the effect of the moon is not important.

128. In principle, infra-red astronomy, could also be endangered by the radiation emitted by the exhaust gases from launching rockets, and especially from those gases that emit near the atmospheric windows used by infra-red astronomers for their observations. However, given the present level of launches of satellites, this danger is not yet regarded as serious.

D. Radio astronomy

129. Many of the astronomical observations which utilize radio telescopes are made at frequencies which are determined not by the choice of the astronomer, but by the natural characteristics of the emitting objects such as clouds of hydrogen in space, and other more complex gases, including those containing carbon which are of special interest since they may provide information about the origin of life. The very weak radio waves which reach the earth from these distant sources can be detected only with the aid of powerful specially constructed radio telescopes. These very sensitive instruments are very susceptible to stray radiation from many manmade sources: broadcasting and television transmitters, radio communication stations, radio aids to air and sea navigation, etc. The frequencies allocated to each of these services are decided during World Administrative Radio Conferences which are held at infrequent intervals and are convened by ITU. Radio astronomy has been formally recognized by ITU as a radio service, and hence it is possible for the needs of radio astronomers for frequency allocations to be taken into account and for allocations to other services to be made in such a way as to minimize the interference likely to be caused to astronomical observations. Even when all possible precautions have been taken in siting a radio-astronomical observatory, so as to limit interference from terrestrial radiating sources, the instruments will not be immune to interference from satellites carrying radio transmitters of any kind. Special attention is, therefore, necessary when allocating frequencies to satellites which radiate; their allocations must be as far as possible from those used by radio astronomers.

130. It is important to bear in mind also that a radio transmitter which operates nominally within a given band of frequency may, in fact, also emit radiation above and below this band. Unless special precautions are taken, it will also radiate at "harmonic" frequencies: that is, at frequencies that are two, three, four, etc., times the fundamental frequency. It follows that a satellite which emits harmonics can cause interference to radio astronomy at frequencies very far from the nominal operating frequency of the satellite. The limitation of these "unwanted" frequencies requires careful attention during the design stage of the transmitter if interference to radio astronomy, and indeed to other types of radio service, is to be avoided or at least reduced to a minimum.

131. The future survival of radio astronomy will depend on the degree of co-operation between the radio scientists on the one hand, and the designers and users of satellites on the other. The reduction to a minimum of the "unwanted" out-of-band and harmonic radiation emitted by satellites will be of particular importance. These questions are considered in ITU and its International Radio Consultative Committee (CCIR).

132. The SPS also deserves mention here in view of the very large radio power it is proposed to generate (6,000 MW). Since spurious emissions are possible, these represent a potential danger to radio astronomy. The large physical size of this satellite implies also that it will be capable of acting as a passive reflector of radio waves emitted from the ground, or possibly from other satellites. Its reflecting power is estimated to be about a million times that of any other satellite at present in orbit.

133. In this connexion it should be noted that a small satellite at, for example, 500 km height would cause interference to radio astronomy if it were illuminated by a 3 kW transmitter at a distance of 2,500 km. Although this is not at present a serious source of interference, with the rapidly increasing numbers of satellites and other passively reflecting objects in space, the problem could become serious in future.

VI. CONCLUSIONS

134. The current level of space activities does not appear to be having any extensive, long-term undesirable effects on the earth or space environment. This conclusion, however, must be tempered with reservations due to a limited understanding of many environmental processes.

135. Upper atmospheric processes in particular are still poorly understood and subtle changes in long-term balances cannot be excluded. It is not inconceivable that slow cumulative changes have been initiated that might continue for some time even if the activity causing the changes were stopped.

136. It does not appear that activities being planned for the next decade will significantly change the situation, but the development of large numbers of large space structures would require detailed study of possible environmental effects.

In particular, the proposed Solar Power Satellite System will require detailed study of the effects of the huge space transport system required for construction, and of the high power microwave beam used to transmit power to the surface.

137. Accidents are and will continue to be a small but real risk, primarily arising from launch and re-entry. When nuclear power systems are involved the risk becomes higher and more widespread. Clearly every effort should be made to reduce accidents and limit the damage that can be caused.

FIGURES

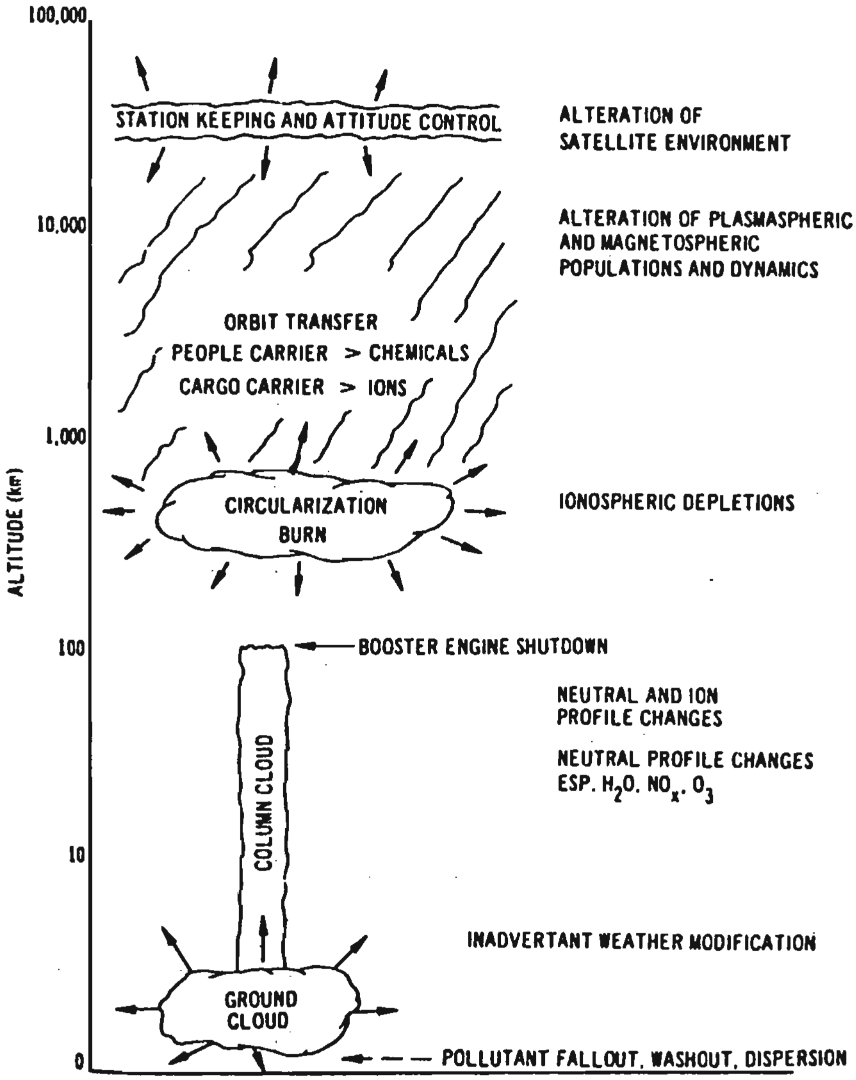

Fig. 1 Summary of Some Potential Atmospheric Effects caused by Rocket Exhaust

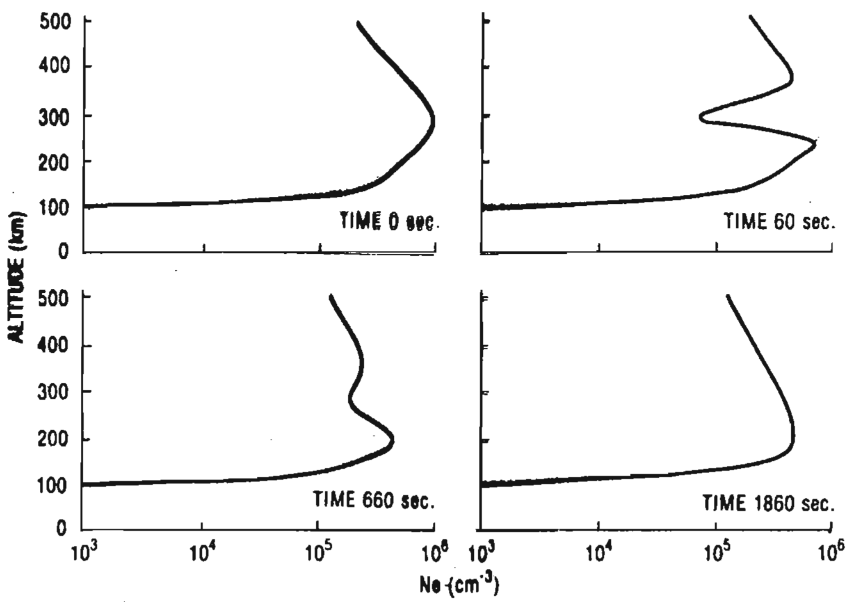

Fig. 2 - Day-time F. Region profiles after hydrogen injection

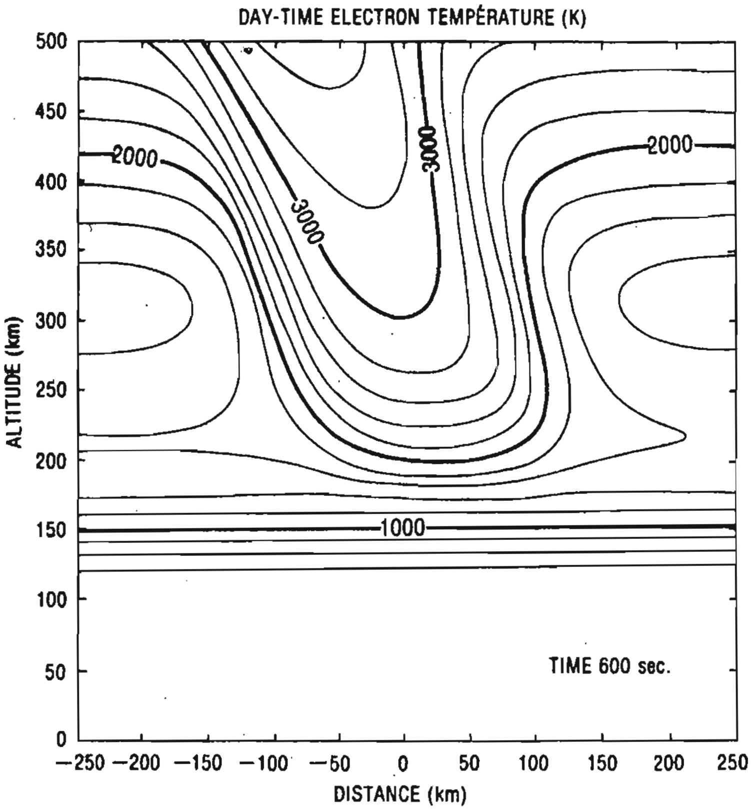

Fig. 3 - Isothermal contours 10 min. after injection

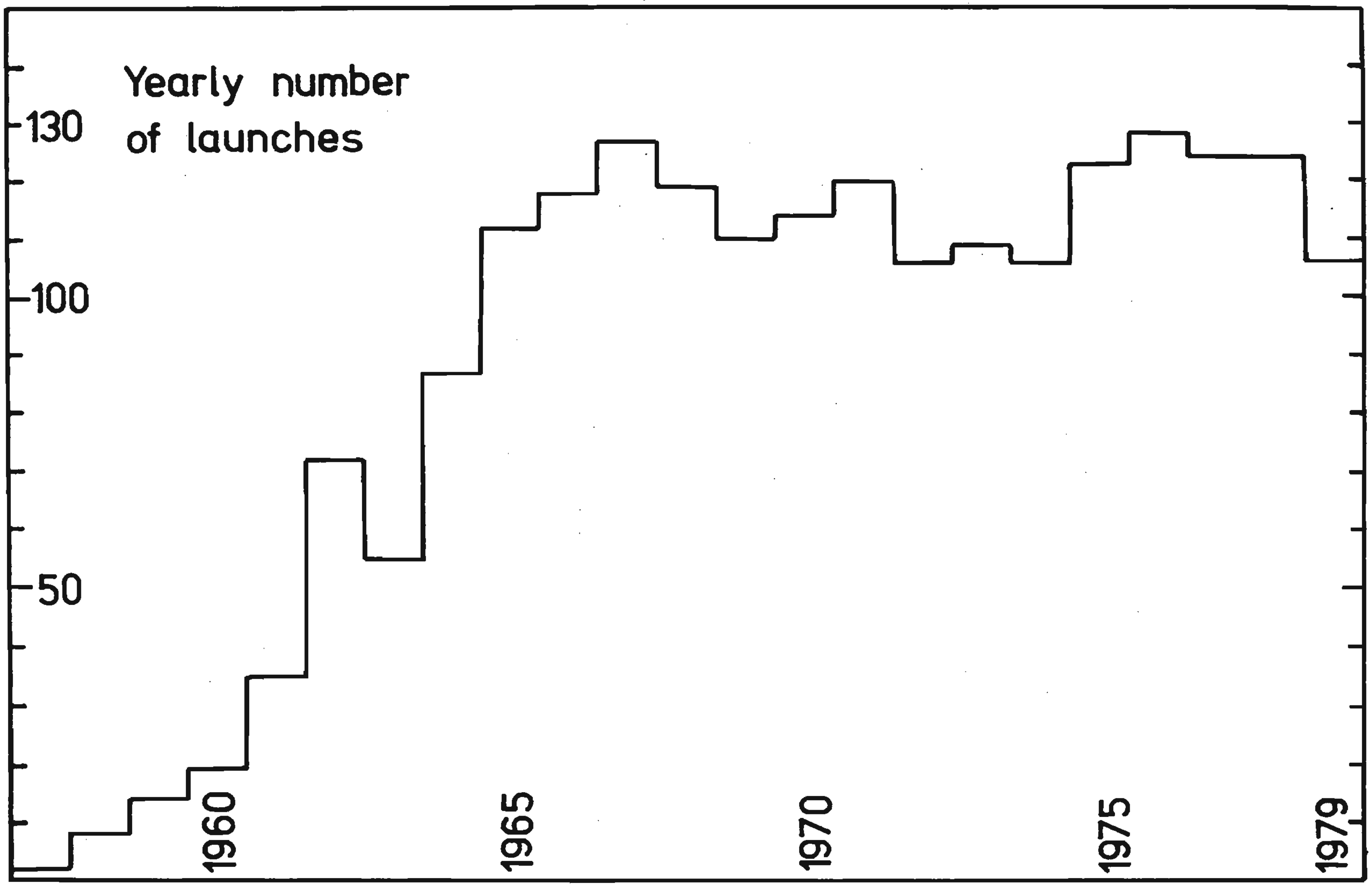

FIG. 4 YEARLY NUMBERS OF SATELLITE LAUNCHES 1959-1979.

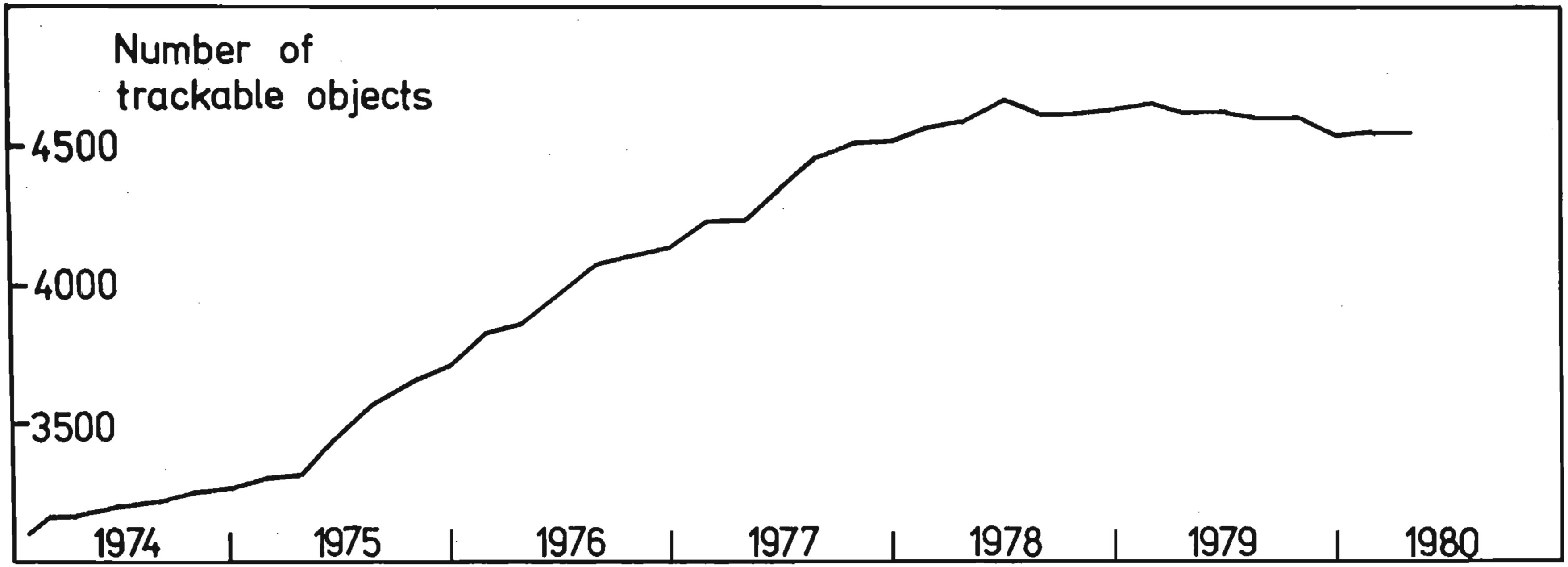

FIG. 5 NUMBER OF TRACKABLE OBJECTS IN OUTER SPACE.

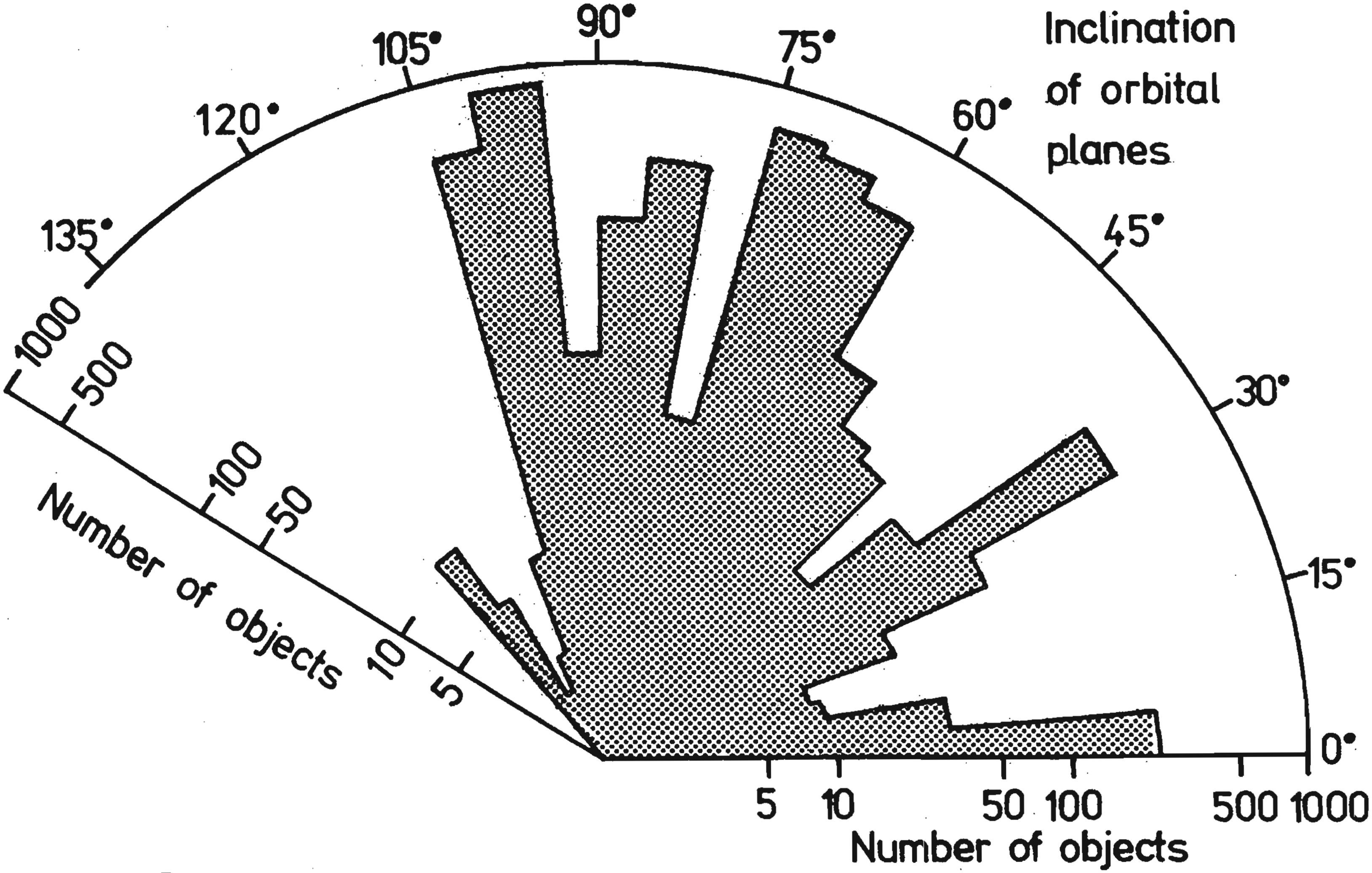

FIG. 6 DISTRIBUTION OF INCLINATIONS OF SATELLITE ORBITAL PLANES

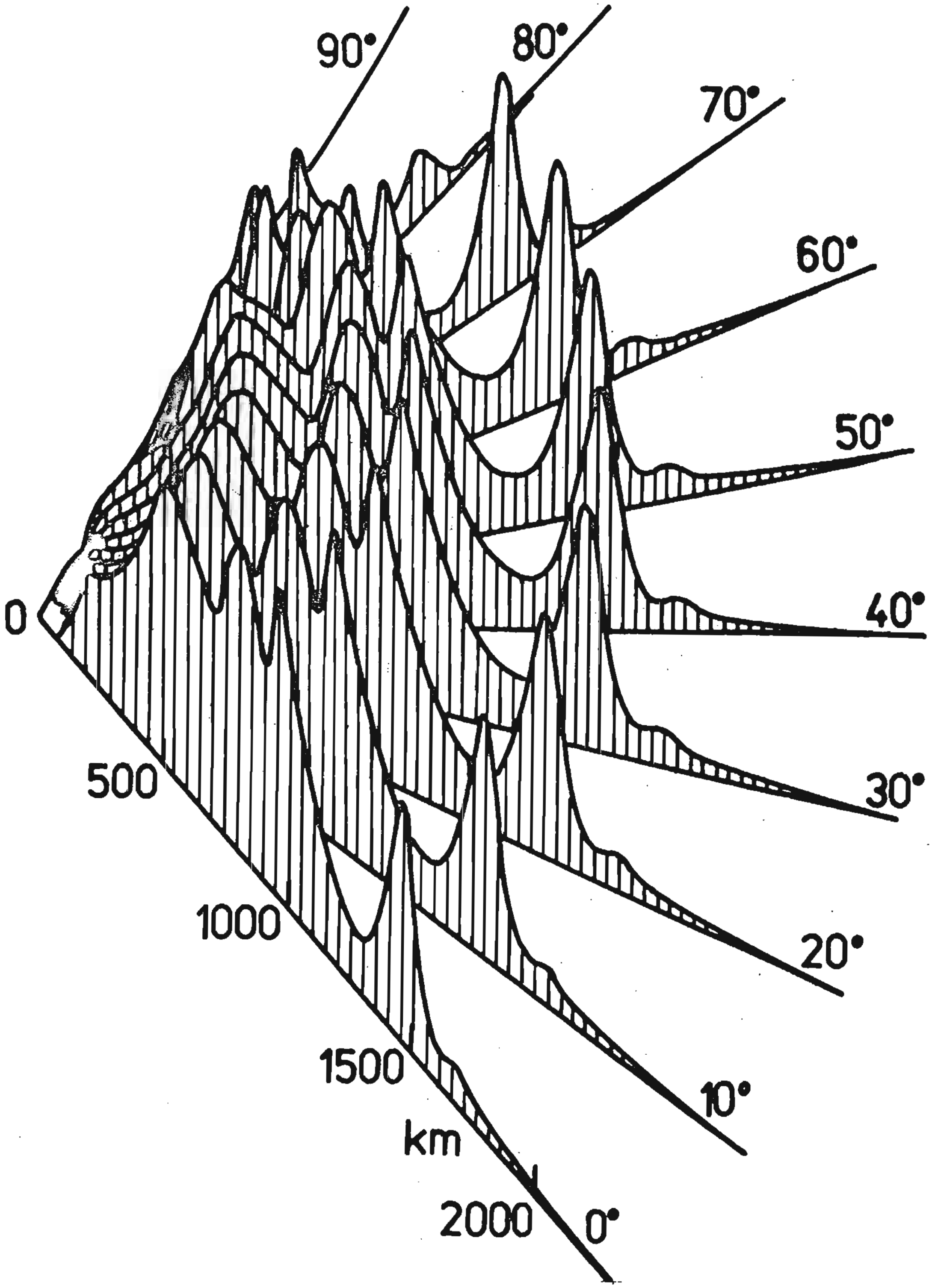

FIG. 7 HEIGHT PROFILES OF SPATIAL DENSITY OF EARTH-ORBITING OBJECTS AT VARIOUS GEOGRAPHICAL LATITUDES.

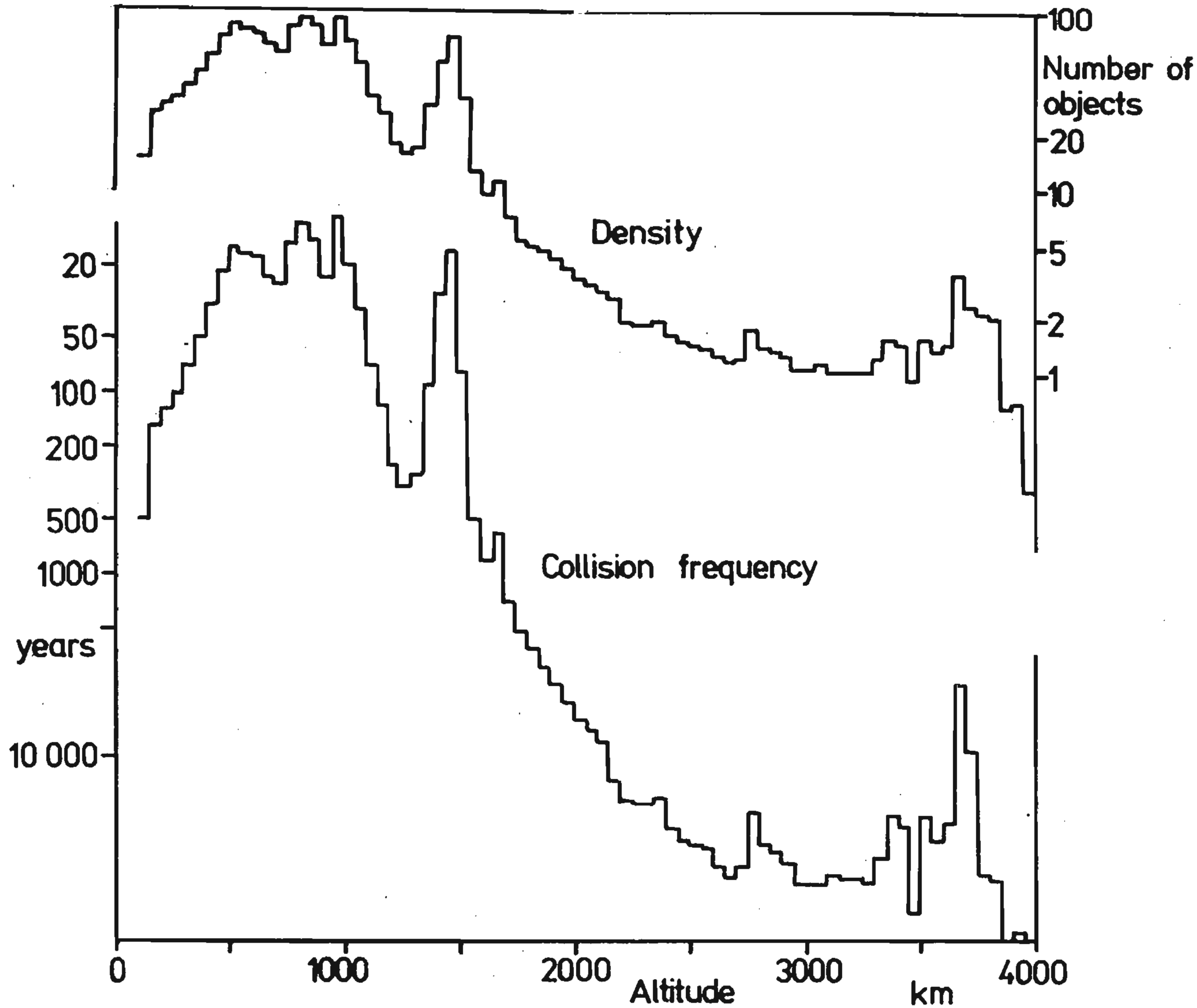

FIG. 8 SPATIAL DENSITY OF EARTH-ORBITING OBJECTS NEAR THE EQUATORIAL PLANE (UPPER CURVE). THE SCALE ON THE RIGHT-HAND SIDE GIVES THE NUMBER OF OBJECTS PER REFERENCE CUBE, OF SIDE 1000 KM. THE LOWER CURVE GIVES THE COLLISION FREQUENCIES AT VARIOUS ALTITUDES. THE SCALE ON THE LEFT-HAND SIDE GIVES THE NUMBER OF YEARS THAT WILL ELAPSE BEFORE A COLLISION CAN BE EXPECTED.

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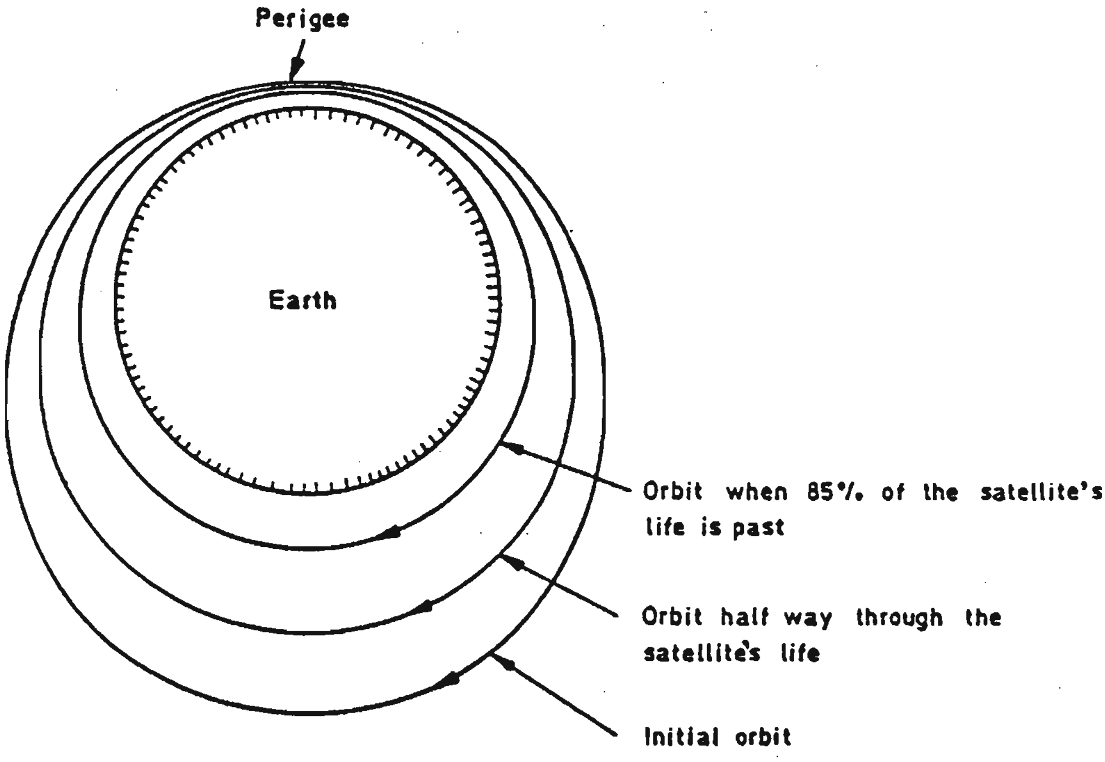
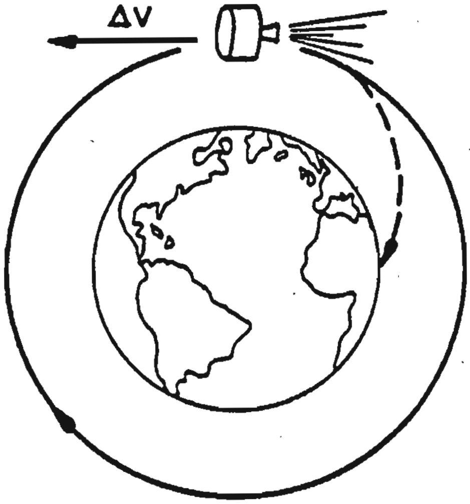
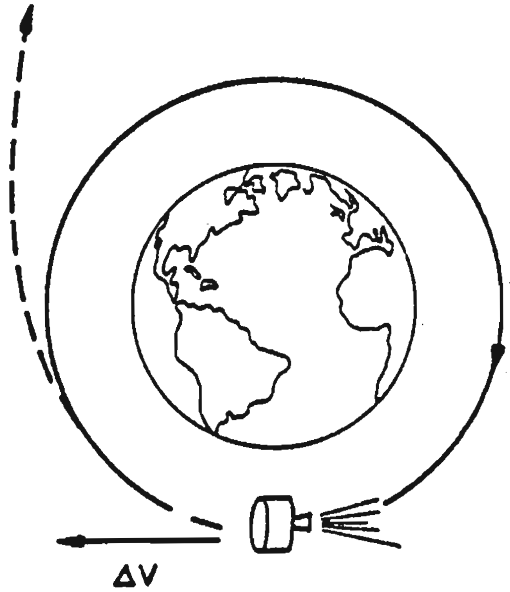


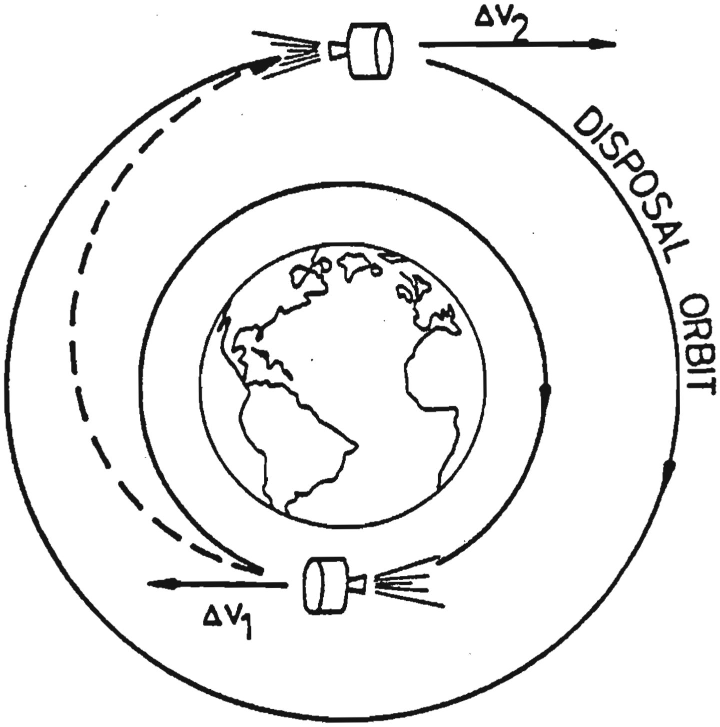
FIG. 9 DIAGRAM SHOWING THE EFFECT OF AIR DRAG ON A SATELLITE ORBIT



a) INTO THE ATMOSPHERE



b) OUT OF THE EARTH'S INFLUENCE



c) INTO A DISPOSAL ORBIT

FIG. 10 THREE METHODS OF A SATELLITE'S REMOVAL FROM ORBIT

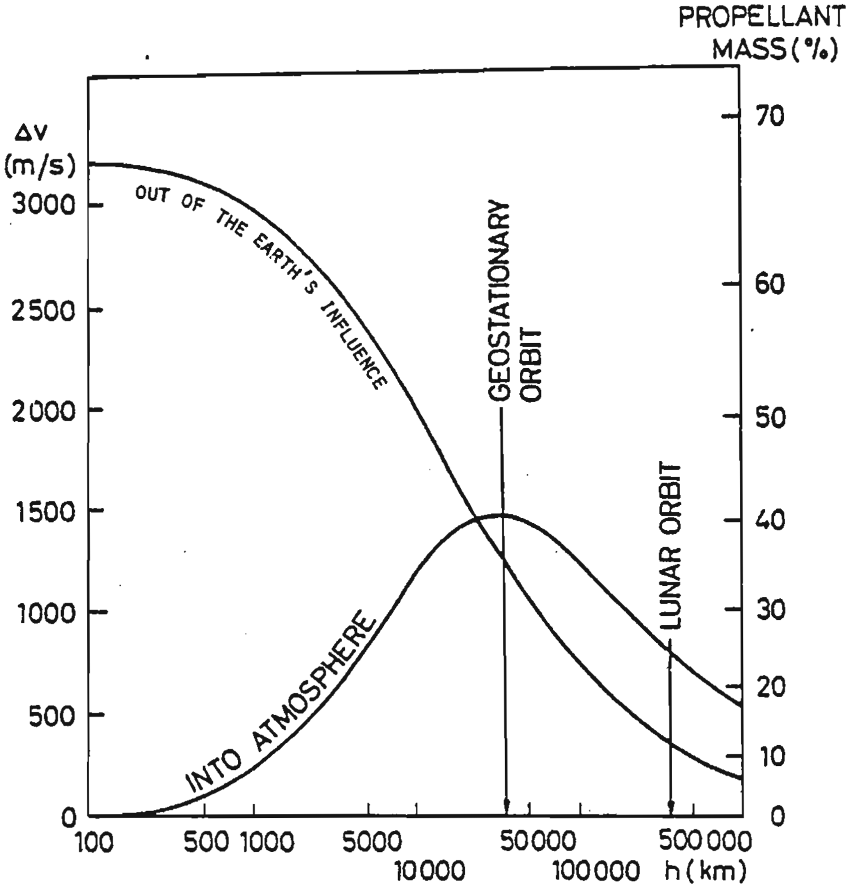


Fig. 11 Mass of propellant and velocity necessary to push the satellite into the atmosphere or out of the Earth's influence.

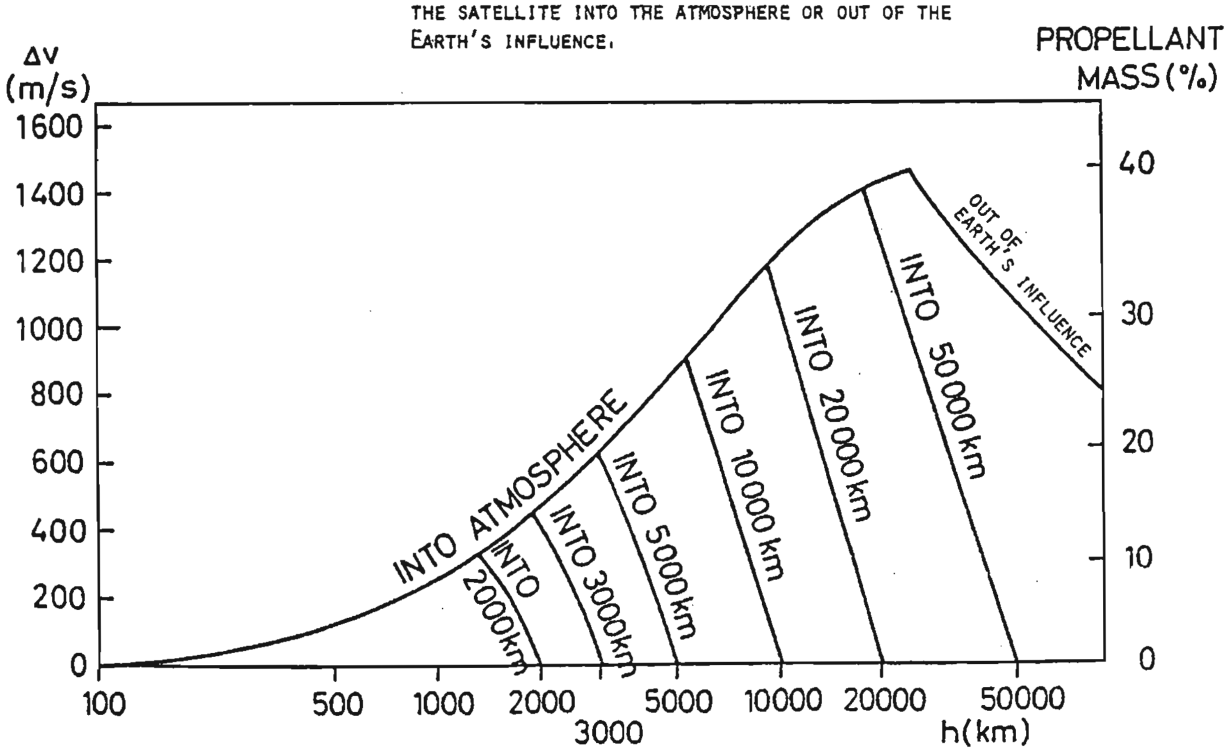


Fig. 12 Proposed methods of a satellite's removal from orbit as a function of altitude.

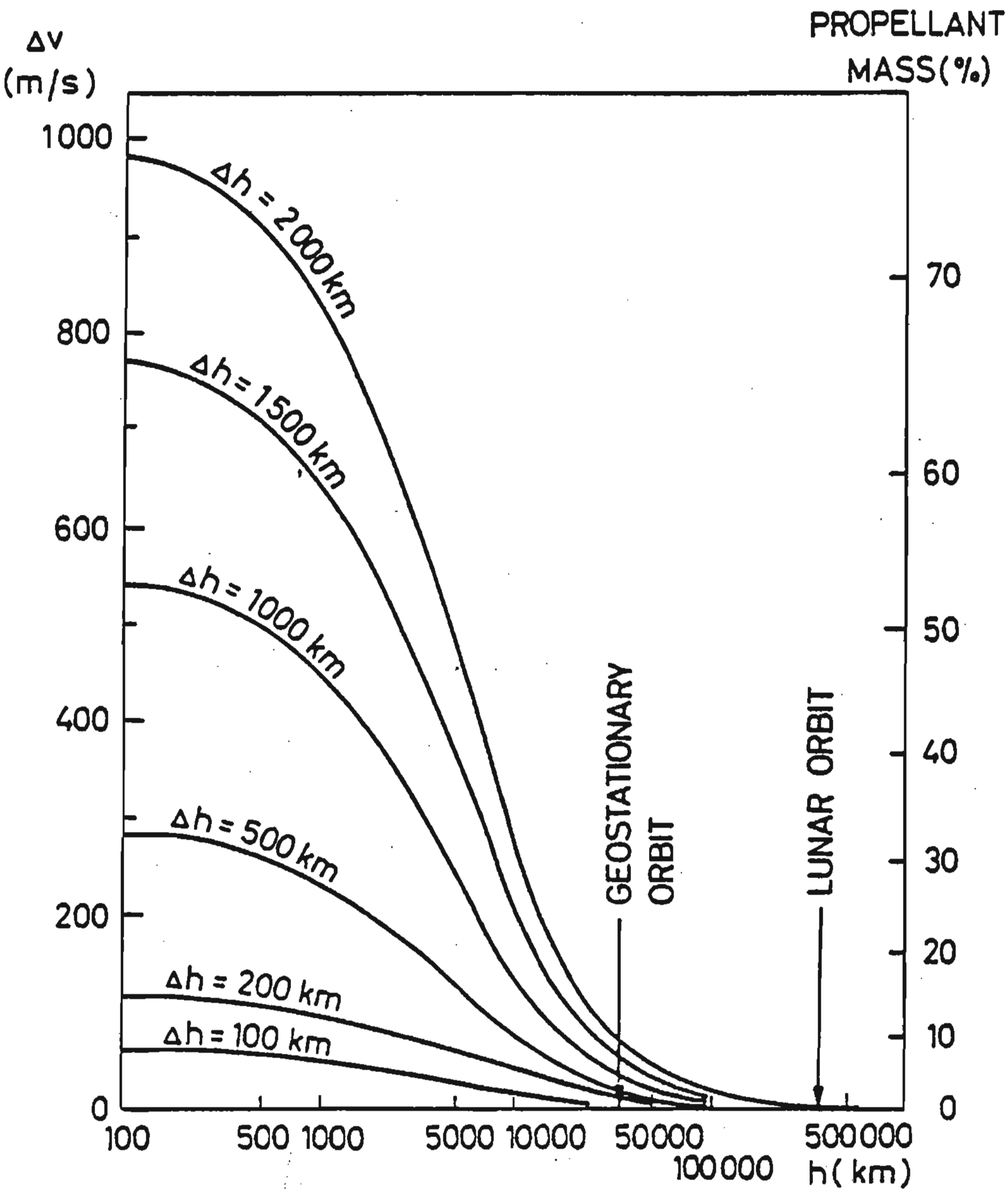


FIG. 13 MASS OF PROPELLANT AND VELOCITY NECESSARY TO INCREASE THE HEIGHT OF A GIVEN CIRCULAR ORBIT.

Annex I

STABILITY OF SATELLITE ORBITS

A. Forces acting on a satellite

1. A satellite in orbit around an isolated spherical planet with no atmosphere would follow an elliptical orbit, without variation, for thousands of revolutions. For the planet earth, however, this simple picture is greatly altered due to three different perturbing forces:

(a) The variation of the earth's gravitational attraction which results from the flattening of the earth at the poles, and other deviations from spherical symmetry, such as the "pear shape" of the earth.

(b) The air drag caused by the rapid movement of the satellite through the tenuous upper atmosphere.

(c) The forces due to the sun and moon, mainly their gravitational attraction, but also the effects of solar radiation pressure.

2. For most satellites, these are the three types of force which cause major changes in the orbits. Many other perturbations exist, but these do not cause major changes; they are caused by: upper atmosphere winds; solar radiation reflected from the earth; earth tides and ocean tides; the precession of the earth's axis in space; resonances with the earth's gravitational field; and relativity effects. It should, however, be noted that these perturbations can become important for particular satellite orbits such as the orbits of balloon satellites.

B. The elliptic orbit

3. The size and shape of the ellipse are defined by its semi-major axis, a, and its eccentricity, e, as shown in figure 1. As the satellite, S, moves in its orbit, its nearest approach to the earth occurs at the perigee, P. The furthest distance of the satellite from the earth is reached at the apogee, A.

4. The orientation of the orbital plane in space is defined by the right ascension of the ascending node, Ω, and the inclination to the equatorial plane, i, as shown in figure 2, relative to a sphere with its centre at the earth's centre, C.

5. Finally, the orientation of the orbital ellipse within the orbital plane is specified by the argument of perigee, ω which is the angle NCP in figure 2.

6. These five parameters, together with a sixth parameter which specifies the position of the satellite in its orbit at a given time, provide a complete description of the motion of a satellite in an unperturbed elliptic orbit. The

position can be specified by the angle PCS in figure 1, denoted by θ, and known as the true anomaly.

7. The five parameters, a, e, i, Ω, ω, together with θ at a given time, are known as orbital elements. More generally, orbital elements are any set of parameters which describe the orbit as fully as those given above.

C. Perturbations of satellite orbits

1. Earth's gravity

8. The earth is not exactly spherical, as it is appreciably flattened at its poles: the equatorial radius is 6,378.14 km, while the polar radius is only 6,356.79 km. Because of this flattening of more than 21 km, the gravitational attraction of the real earth is slightly different from that of a sphere and, as a result, the elliptic orbit of a satellite suffers some changes. Although its size and shape remain almost the same (the changes in a, e, and i being small), the orbit is no longer fixed in space. The orbital plane rotates about the earth's axis, with the inclination remaining constant. If the satellite is heading eastwards, the orbital plane swings to the west, as shown in figure 3, and the right ascension of the node, Ω, steadily decreases. These effects are quite significant for satellites close to the earth.

9. Most satellite orbits have inclinations less than 90° and thus travel eastward while their orbital planes swing from east to west. The rate of change of Ω depends on the inclination, e; for a near-equatorial orbit, the rate is about 8 degrees per day. For an orbit at inclination 60°, the rate is 4 degrees per day, becoming zero for a polar orbit.

10. In addition to this movement of the orbital plane, the orientation of the orbit within the orbital plane also changes, so that the perigee latitude is continually changing. For a near-equatorial orbit, the perigee moves in the same direction in which the satellite is travelling, at a rate of about 16°/day; for a polar orbit, the perigee moves in the opposite direction from the satellite at about 4°/day. For an orbit at an inclination of 63.4°, often called the critical inclination, the perigee remains at a fixed latitude.

11. Because of these two effects, a satellite eventually passes through points within a toroidal volume bounded by its perigee and apogee heights, and a maximum latitude north and south, which is equal to the inclination, as shown in figure 4.

12. Although the earth's flattening is its greatest deviation from a sphere, there is also a slight asymmetry between the northern and southern hemispheres. Sea levels at the North Pole and the South Pole would differ by 44 m. This asymmetry is usually called the pear shape effect. It causes slight changes in the shape of the orbit of a satellite, producing an oscillation in the orbital eccentricity, e, which leads to an oscillation in the perigee distance although the semi-major axis, a, remains constant. This oscillation can have an important effect on perigee height.

13. These effects are the most important perturbations for low orbit satellites. However, for satellites in higher orbits, such as geosynchronous orbits at a height of approximately 36,000 km, the effect of the earth's oblateness is very much smaller, and the variation of the gravitational field with longitude rather than latitude becomes more important.

2. Air drag

14. The density of the upper atmosphere decreases exponentially with height above the earth's surface, and is only about 10 gram/cubic kilometre at a height near 350 km. However, a satellite moves at a speed of nearly 8 km per second, and its collisions with the air molecules are frequent enough to create a considerable drag force.

15. If the orbit is non-circular, the air drag is much greater at perigee than at apogee. The satellite is thus retarded at perigee, and does not fly out as far as expected at apogee. Hence, the orbit contracts with a tendency to become circular.

16. If the orbit is initially circular, air drag acts continuously along the orbit, thus reducing the height of the orbit gradually.

17. For both circular and elliptic orbits, the drag rapidly increases as perigee height decreases. At perigee heights of about 100 km the satellite can no longer remain in orbit and begins its final plunge into the lower atmosphere.

18. It should be noted that, although air drag retards the satellite at perigee, the over-all effect of air drag is to make the satellite move faster. Its orbital period decreases as its lifetime progresses, and final decay usually occurs when the orbital period has decreased to about 87 minutes.

3. Luni-solar gravity

19. Both sun and moon exert small gravitational attractions on satellites, and therefore perturb satellite orbits because these small attractions combine with the main attraction of the earth and change its amount and direction differently at different points of the orbit. In general, lunar gravity is about twice as effective as solar gravity in perturbing satellites in low earth orbits.

20. For a satellite close to the earth, luni-solar gravitational perturbations produce small oscillatory changes in all the orbital elements except the semi-major axis. For most near-earth satellites the effects are quite small, displacing the satellite by less than about 2 km at periods ranging from about 10 days to more than a year.

21. The complete luni-solar perturbation is made up of many different terms, each with its own period. It is quite likely that one or more of these periods may

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be very long, perhaps several years, and perturbations building up for several years may become much larger than expected. For example, a perturbation may only amount to 10 m/day, but if it continues for 500 days, it will amount to 5 km.

22. For satellites in higher orbits, luni-solar perturbations are of greater importance, being approximately proportional to the orbital period, for given eccentricity and inclination. For synchronous orbits, with orbital periods of 1,436 minutes, the effects are considerable.

23. An increase in eccentricity also increases the effect of luni-solar perturbations, and these are particularly severe for the many Molnya satellites having eccentricities near 0.7 and orbital periods near 720 minutes.

4. Solar radiation pressure

24. The pressure of solar radiation is very small (4.6×10^{-6} newtons/m^2), but its effect on satellite orbits can be appreciable.

25. The acceleration of a satellite as a result of solar radiation pressure is directly proportional to the satellite's cross-sectional area divided by its mass, the area/mass ratio. A satellite constructed of metal usually has an area/mass ratio near 0.01 m^2/kg, and the perturbations due to solar radiation pressure are very small, less than 1k km.

26. For a balloon satellite, however, the area/mass ratio and the perturbation can be a thousand times greater. For the Echo 1 balloon, the area/mass ratio was about 10 m^2/kg, and the main solar radiation pressure perturbation had a long period, about 20 months, with the result that the perigee height of Echo 1 oscillated with an amplitude of 500 km.

27. Even for satellites with low area/mass ratios the effects of solar radiation pressure can exceed the effects of air drag at heights above 500 km, though both effects are small at these altitudes.

D. Special orbits

1. Geosynchronous orbits

28. An orbit is called geosynchronous if the satellite moves at the same angular rate and in the same direction as the rotating earth. It completes one revolution in one sidereal day and its semi-major axis, a, has to be equal to 42,160 km. Viewed from the ground, such a satellite would be seen to complete a closed curve on the sky every day. The shape and dimensions of the curve depend on all orbital elements (see paras. 3-7) with the exception of a, which is fixed. Generally, the smaller the inclination and eccentricity of the orbit, the smaller the apparent curve on the sky. In the extreme case, for a circular orbit in the equatorial plane (zero inclination and zero eccentricity) the curve shrinks to a point and the

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satellite is seen in a fixed direction. Natural perturbations, however, force the satellite out of the ideal geostationary orbit. Only by artificial "station-keeping" manoeuvres can the satellite be kept reasonably close to the ideal geostationary orbit.

29. Because of the enormous importance of geostationary satellites for communications, meteorology and other applications, a separate background paper (A/CONF.101/BP/7) has been devoted to the efficient use of the geostationary orbit.

2. Integer orbits

30. By choosing suitable values for a, or, which is equivalent, for its mean altitude above the earth, a satellite can be made to pass daily along certain strips of the earth's surface, leaving other areas uncovered. These orbits are called integer orbits with N revolutions per sidereal day. Thus, e.g., satellites at altitudes of 554 km, 881 km and 1,248 km in polar orbits would complete 15, 14 and 13 revolutions per sidereal day respectively.

3. Sun-synchronous orbits

31. By choosing suitable values of the altitude and inclination of the orbit the movement of the orbital plane (see paras. 8-9) can be made to compensate for the annual movement of the sun in the ecliptic. Such a satellite would cross the equator always at the same local time. This was found very useful for earth observation satellites which then provide imagery of individual regions under nearly the same illumination by the sun. Thus, e.g., satellites at altitudes of 565 km, 893 km and 1,261 km and inclinations 97.6, 99.0 and 100.7 would complete 15, 14 and 13 revolutions per day respectively.

32. Sun-synchronous orbits can also be achieved by using the attraction of the moon. A satellite proposed, e.g., for the study of the geomagnetic tail, which from the earth, is opposite to the direction of the sun, is made to spend most of its time in the tail region by a double approach to the moon, as shown in figure 5.

4. Highly eccentric orbits

33. The laws of dynamics show that a satellite spends much more time near the apogee of a highly eccentric orbit than near its perigee. Also, its apparent movement in the sky is rather slow near the apogee. This has been used with advantage for communication satellites at high geographic latitudes. A typical orbit of this kind has an inclination of about 63, a perigee at 400 to 500 km and an apogee at 40,000 km which is slightly beyond the altitude of geosynchronous satellites, and a period of exactly half a day. A system of four satellites has been designed in such a way that, from a ground station, one satellite is seen to rise slowly above the horizon and, after reaching maximum elevation, is seen to set slowly on almost the same path in the sky. Just before setting, another rising satellite almost meets the setting satellite; provision is thus made for easy tracking and ready switching of communications.

5. Libration orbits

34. In the earth-moon system, there are five important centres, called Lagrangian libration centres. A satellite placed at any of these centres would retain the same configuration with respect to the earth and moon. The first centre, L_1, lies between the earth and the moon, at about 85 per cent of the distance to the moon. The second centre, L_2, lies beyond the moon, and the third, L_3, lies in a direction opposite to that of the moon. The equilibrium of a satellite in those centres would be unstable, i.e., it would require station-keeping. The most important centres, L_4 and L_5, lie at the apices of equilateral triangles formed by the earth, the moon and the satellite. A satellite at one of these centres would require no station-keeping. This is the reason why the last two centres have been proposed as suitable sites for the first space colonies or habitats.

35. A similar situation is presented by the sun-earth system. Here, the centre L_1 is 1.5 million km distant from the earth in the direction towards the sun. A scientific satellite has been placed near L_1 where it has a vantage point for observing solar activity and providing early warning of incoming charged particle streams from the sun.

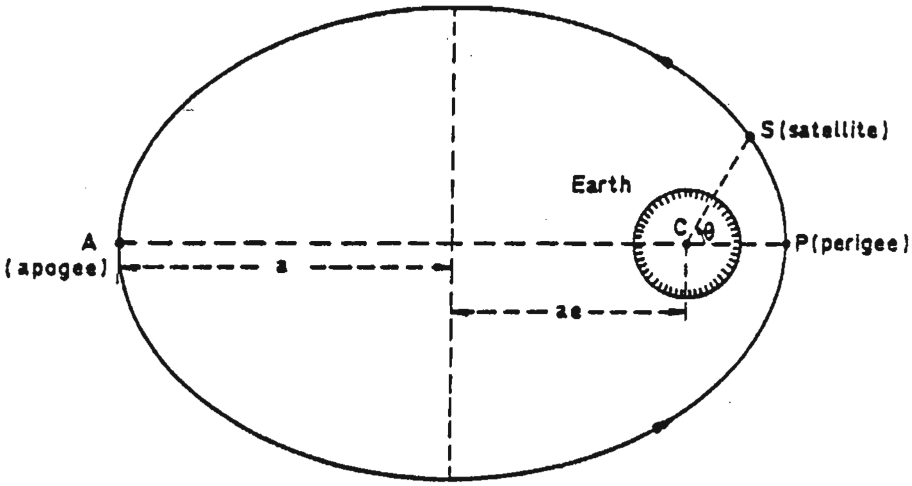

FIG. 1 DIAGRAM DEFINING SEMI-MAJOR AXIS (a) AND ECCENTRICITY (e) OF AN ELLIPTIC SATELLITE ORBIT AROUND THE EARTH

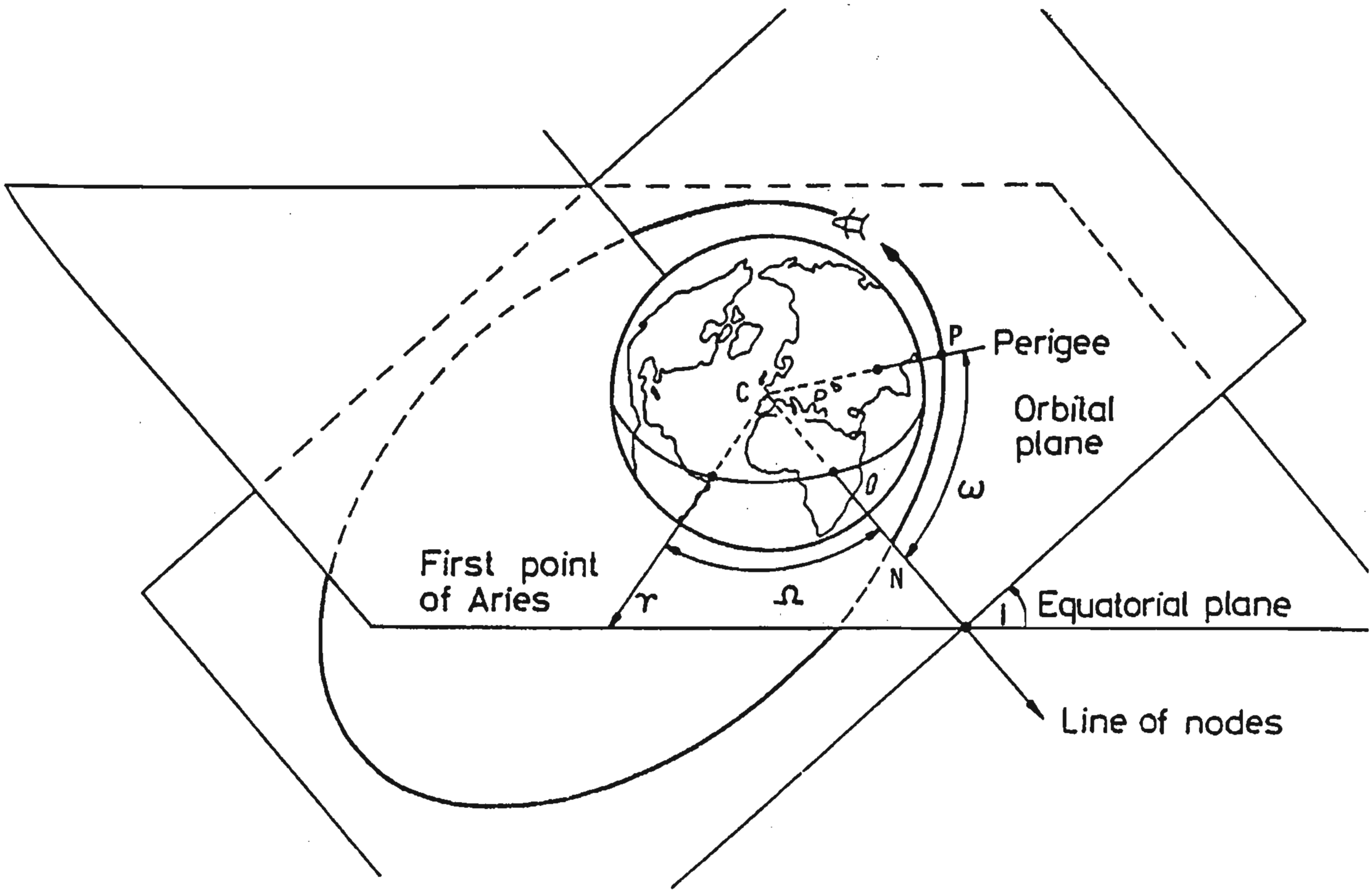

FIG. 2 THE POSITION OF SATELLITE ORBIT IN SPACE SHOWING DEFINITIONS OF THE LINE OF NODES, RIGHT ASCENSION OF NODE Ω, INCLINATION i AND ARGUMENT OF PERIGEE ω.

/...

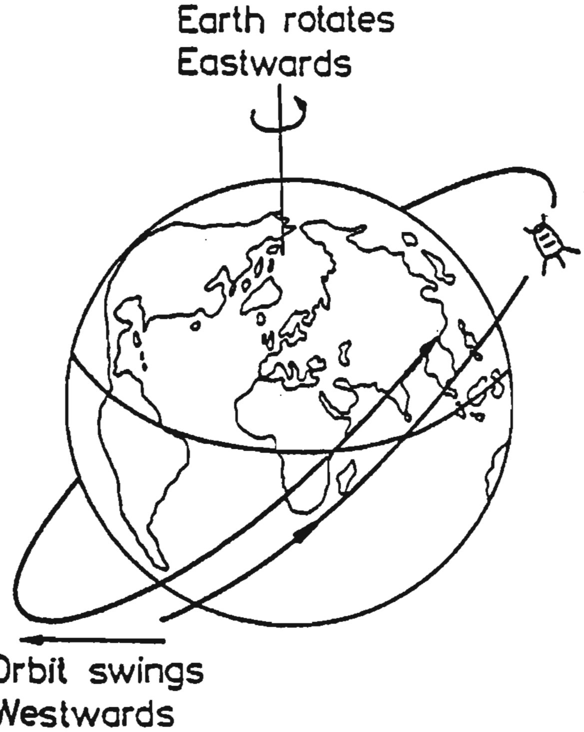

FIG. 3 THE GRAVITATIONAL PULL OF THE EARTH'S EQUATORIAL BULGE CAUSES THE ORBITAL PLANE OF AN EASTBOUND SATELLITE TO SWING WESTWARD.

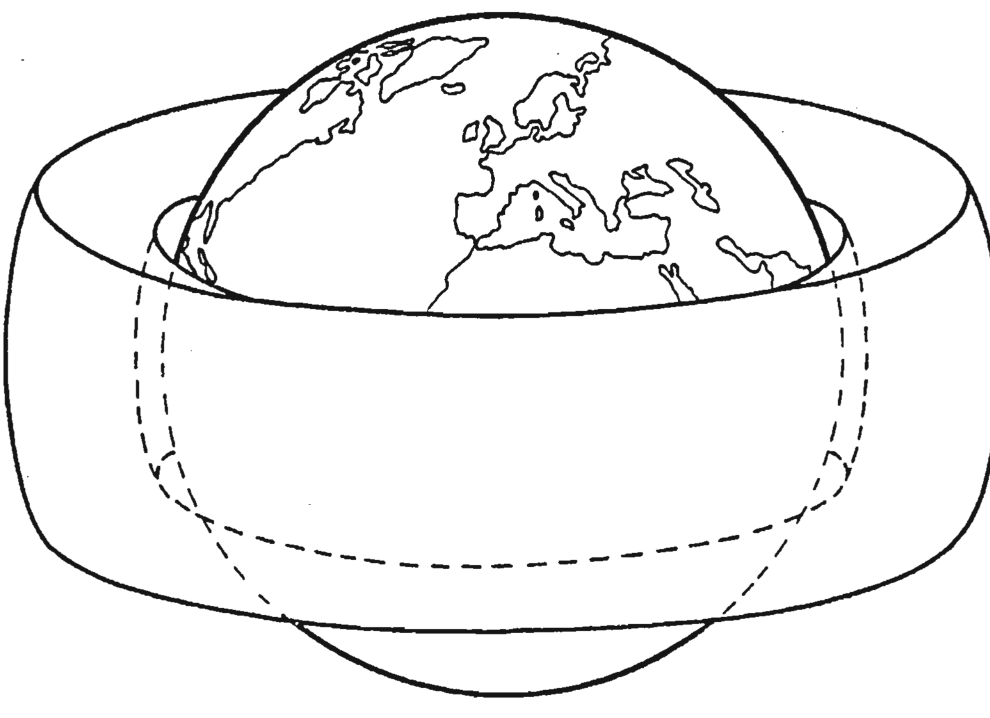

FIG. 4 THE TOROIDAL VOLUME TRAVERSED BY A SATELLITE

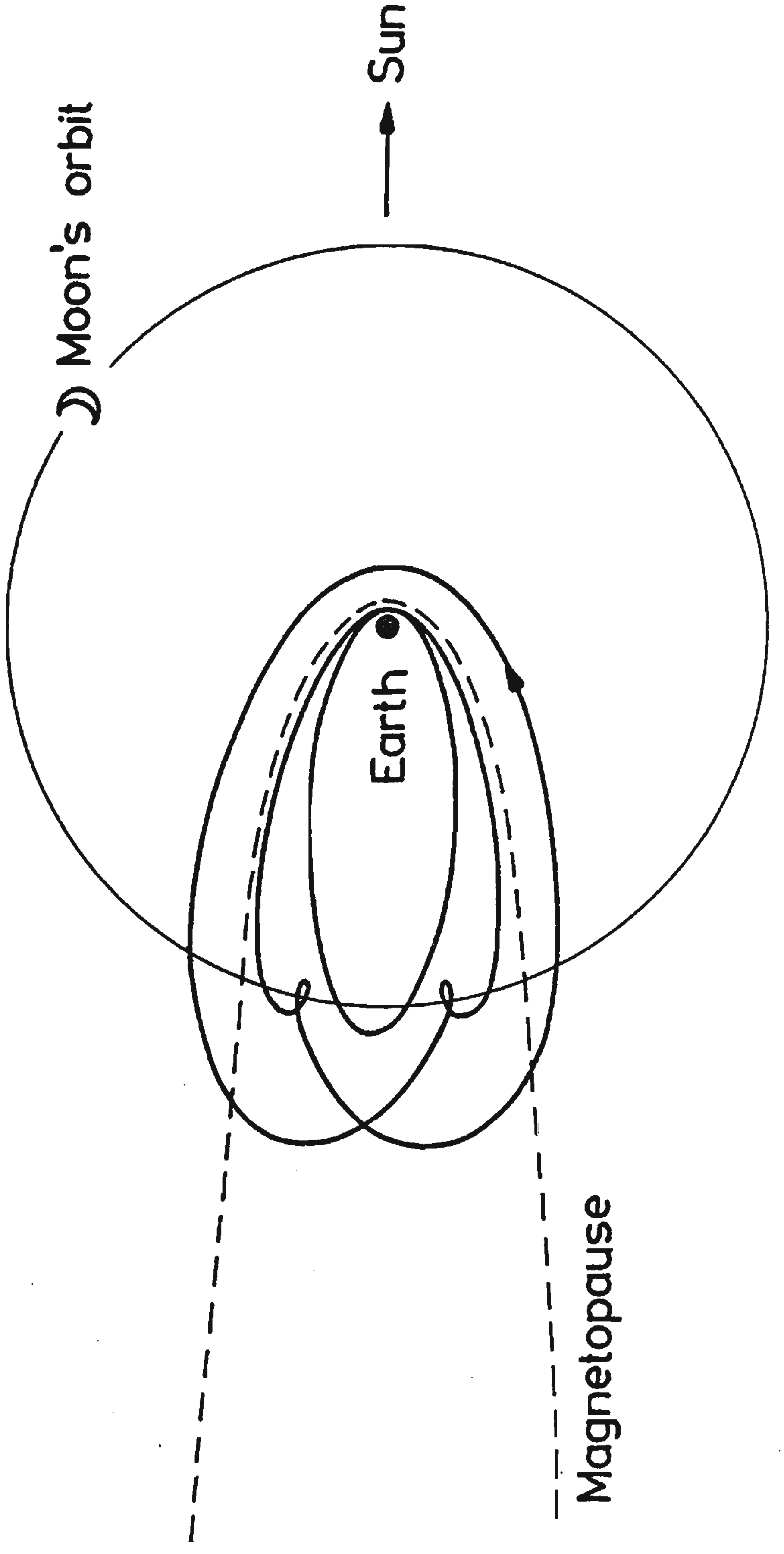

FIG. 5 PROPOSED SUN-SYNCHRONOUS ORBIT FOR GEOMAGNETIC TAIL MISSION.

Annex II

ELECTRICALLY AND MAGNETICALLY ACTIVE RADIUS OF A SATELLITE

A. Concepts and definitions

1. Since there is no exact definition, we suggest that the "electrically or magnetically active radius of a satellite" be understood as the maximum distance at which the electric or magnetic effects of the satellite can be observed. Good indicators of such effects are relative electron or ion density variations which are measurable down to about 0.1 per cent. Therefore, this value was taken as the limit of observable electric effects. Another approach to that limit follows from the threshold of 0.2 gamma (nT) of recent measurements of natural variations of the local magnetic field at elevations of about 1,000 km. There are also other physical parameters which would serve the purpose of defining the limit of observable effects. Referring to electric and magnetic effects of one spacecraft on other satellites, the limit of observable effects would be defined by the sensitivity of the sensor and onboard receiving device and/or by the characteristics of the naturally occurring variations.

2. An important plasma characteristic, defining the electric radius of a satellite, is the Debye radius, D, i.e. the distance beyond which the ambient electric charges fully screen the electric field due to a given point charge. This is closely related to the penetration of the satellite electric field into the surrounding plasma, and defines the thickness of the plasma sheath around the satellite. On the other hand, the plasma sheath alters the electric field distribution around the satellite and the charged particle trajectories within the screening zone. It is important to consider the mutual dependence between the charge and potential distributions both over the satellite surface and in the plasma sheath.

3. In terms of the disturbing effects on terrestrial systems of satellite electric and magnetic fields due to onboard energy sources, the most important are the effects of the planned solar power satellites (SPS) on ground communications and on aircraft that might pass through the beams of electromagnetic energy between the spaceborne energy sources and the ground receiving stations. The documents of the CCIR of ITU have treated the present situation of satellite communications and radio systems excellently.

B. The plasma environment

4. The electric (R_E) and magnetic (R_M) radius of a satellite, when there is no onboard electromagnetic source, is defined by the interaction between the satellite and the space plasma environment. For earth satellites, this environment is a partially or almost fully ionized multicomponent gas having large spatial variations of its characteristics. In space surrounding the earth, of interest to this study, the plasma density varies from about 5×10^6 cm^{-3} to about 1 cm^{-3}, and the particle thermal energy from 0.2 eV to 30-40 eV.

1. Ionosphere

5. The ionosphere is considered to extend up to about 1,000 to 1,500 km, where transition to the phasmasphere occurs. The major ion of the ionosphere is atomic oxygen, with a density ranging from 10^3 cm^{-3} to 5×10^6 cm^{-3} for quiet midlatitudinal conditions. Normally, the electron temperature exceeds 3,000 K, while the ion temperature varies with altitude during the daytime from about 1,500 K at 300 km to about 2,500 K at 1,000 km.

2. Plasma environment at geosynchronous orbits

6. The dynamic behaviour of the plasma environment near geostationary orbit (altitude 36,000 km) is extremely complicated. The spatial and temporal variations cannot be defined either in a purely theoretical manner or based on experimental data from one satellite only. An over-all model for the environment at geostationary orbit necessarily needs models for the electric and magnetic fields, plasma composition and density, charged particle fluxes and flux density, charged particle energy spectra and other parameters. The typical parameters of the geosynchronous plasma environment depend strongly on geomagnetic activity. The number density varies between 0.5 and 150 cm^{-3}. A mean free ion path of 10^6 km, a Larmor ion radius of 1,000 km, and a Debye radius of several tens of metres to 1 km can be considered as representative values.

7. Solar ultra-violet and X-radiation also determine to a great extent the interaction between a satellite and the surrounding environment. Depending on the photoemission characteristics of the spacecraft surface materials, the sunlit part of a spacecraft can be charged to a high positive potential. Satellite charging to negative potentials occurs preferentially on non-illuminated surfaces or during an eclipse, at the spacecraft, of the sun by the earth.

C. Electric and magnetic satellite radius

8. Satellite-environment interactions are either passive, when the environment affects the satellite and causes it to charge up, or active, caused by the operation of the spacecraft disturbing the environment.

9. Interaction between the environment and the satellite surface occurs via charged particle fluxes to and from the satellite surface and via solar illumination. The following particle fluxes contribute to the interaction: primary (magnetospheric) electrons and ions, photoelectrons, secondary electrons from electron and ion collisions with the surface and backscattered electrons. As a result of this passive interaction, the spacecraft becomes charged. Problems related to the degree of charging refer directly to the electrically active radius of the spacecraft.

1. Spacecraft charging at geostationary orbits

10. The Debye radius in the outer magnetosphere is of the order of 1 km, and is large compared to the satellite size. In the presence of high energy electron fluxes, the dark shadow side of a satellite may be charged to a very high negative potential. If these electron fluxes are small compared to the photoemission current, insulated surfaces on the sunlit part may acquire a positive potential.

11. For a sufficiently large Debye radius and low photoemission current, it may be suggested that the total charge of the photoelectron cloud is small compared to the surface charge of the satellite. The behaviour of the plasma sheath around the spacecraft is then complex. Experimental results on the degree of charging of the ATS-5 satellite show that the average surface potential is -2 kV, and the maximum -10 kV. The ATS-6 satellite was charged, on average, up to +4 kV and even up to +20 kV. The largest potentials were observed during solar eclipses; there is also direct correlation between the degree of charging and the geomagnetic activities.

2. Spacecraft charging at low orbits

12. For low altitude satellites, the satellite velocity is much greater than the ion thermal velocity and much smaller than the electron thermal velocity. This results in a region of increased plasma density being formed in front of the satellite, while behind it there is a wake, a long region of low-density plasma. Due to their greater mobility over ions, electrons tend to fill the space behind the satellite. The quasi-neutrality of the plasma near the satellite surface is disturbed; a double layer with dimensions of the order of several Debye radii is formed as the potential over this distance drops from its value on the satellite surface to that of the non-disturbed plasma. Comparisons show that measured electron and ion densities agree well with theory. In the case of Explorer-31, it was found that plasma quasi-neutrality in the wake was attained within a distance as little as about twice the satellite radius (2 Ro) at an altitude of 400 to 700 km. Measurements made during the docking of Gemini and Agena give the number density in the wake half that of the undisturbed plasma, at a distance of 5 Ro at a height of 400 km. The difference between these two measurements is due to the fact that an increased density of H^+ ions much more effectively fill the region of negative potential behind satellite.

D. Electric and magnetic radius of large space systems and solar power satellites (SPS)

13. When there are sources of electromagnetic disturbance on board a satellite, its electrically and magnetically active radius is defined by the superposition of the fields generated by the sources and the satellite body potentials. Solar panels, along with various types of ion engines, VHF antennas, electromagnetic radiators for research purposes, stabilization systems, etc., are systems which

generate additional electromagnetic fields. Around the large panels of solar cells, used as a source of power for the satellite, there is a plasma sheath, the size of which depends on the Debye radius. At low orbits, the disturbing potential of the solar panel is screened at a distance of several Debye radii. The results of laboratory experiments show that, at a plasma density of about 10^6 cm^{-3} and panel potential of 30 V, the thickness of the disturbed layer is about 30 cm.

14. When large solar panels are designed for a solar power satellite at geostationary orbit, the potential distribution along their surfaces is the key problem. Computer modelling shows that the size of the disturbed zone around the solar panel, with a potential of 40 kV and dimensions of the order of 1 km, is commensurable with the panel size.

15. The use of ion engines becomes more and more important for the propulsion and the stabilization of large space systems. These cause a plasma cloud around the satellite, which affects the satellite's potential. The efficiency of these engines depends on their orientation with respect to the earth's magnetic field lines and on the potential of the spacecraft. In many cases (at low orbits), a significant reverse current flows back to the satellite surface, due to the high plasma conductivity along the magnetic field lines; this results in a reduction of engine efficiency. For powerful energy systems at geostationary orbits, the use of ion engines at the ends of 500 m long booms is planned.

16. Additional disturbances are introduced by powerful emitters of VHF radio waves. At low orbits this results in plasma heating and a corresponding increase of the Debye radius. Onboard emitters of HF and VHF waves generate electric and magnetic fields at large distances from the satellite. Usually, the aerials of these emitters are strictly directional and cause very large electromagnetic fields at their apertures. In the beam direction of the radiation pattern of such an antenna, the electrically and magnetically active radius of a satellite (which may, more appropriately, be named the "electromagnetic" radius) reaches the earth. In the most extreme case of an SPS so far designed, the enormous energy flux may significantly perturb the ionosphere and, when reaching the earth's surface, may even be harmful to the biosphere. The energy fluxes in the side lobes of a relatively poorly directional onboard antenna attain significant values, and increase the electromagnetic radius of the satellite to 1,000 km. Particularly dramatic is the case of an SPS, in that the desired directional properties of the VHF antennas cannot be guaranteed under such great powers; the energy within the side lobes would be sufficient to disturb communications with other satellites and also to affect people and systems on the ground. Especially drastic would be the case were oscillations of a stabilized SPS to occur. This effect would lead to a sharp increase of the size of a disturbed area around the satellite and could alter the operation of other geosynchronous spacecraft, communications systems in particular. For an SPS with 1,000 MW, this disturbed region could extend over several thousand kilometres.

17. Precise calculations of the electrically or magnetically active radius of the satellite would, in this case, require an accurate analysis of the VHF

antennas designed. In principle, the SPS and possible nuclear power stations at geostationary locations, because of their electric and magnetic effects, could affect world communications and navigation systems and may create disturbances to both air and surface transport systems.

18. The electromagnetic radius of the spacecraft is often determined by the telemetry and research emitters of HF and VHF radio signals rather than by the passive interactions between the spacecraft and the surrounding plasma. The boundary values of disturbing fields for these cases can be derived from the regulations of ITU (CCIR).
