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SPECTRUM MANAGEMENT

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ABSTRACT

The radio frequency spectrum is a natural resource, shared by all nations. It is limited and therefore its utilization must be carefully managed. This paper discusses major aspects of the issue, and gives basic information about its international aspects.

1. INTRODUCTION

When Jean-Baptiste Fourier (1768 - 1830) introduced his transforms of mathematical functions and spectrum concept, this was considered only as a curious idea without any practical significance. His concept was criticized and generated lots of doubts. Only after resolving the doubts by Dirichlet and Riemann, the Fourier's approach has found applications in many branches of science and engineering. The term "radio-frequency spectrum" appeared when it has been found that the Fourier spectrum allows for defining conditions of interference-free operation of radio stations.

Today, the radio frequency spectrum is considered as a physical, measurable quantity. The ability to carry energy and messages at a distance at the speed of light made the spectrum of radio waves ------ recognized as a valuable resource. Free access to it, from any place and at any time, made it a common welfare from which everyone can profit. Its role is so important that its use is regulated by an international treaty - the International Telecommunication Convention. One of the articles of this treaty reads: "radio frequencies and geostationary satellite orbit are limited natural resources [...]; they must be used efficiently and economically [...] so that countries [...] may have equitable access to both" ([14], Art. 33-154). The demand for the spectrum is greater than its available capacity, and this involves economic consequences and legal, political, technical and organizational problems. A rational spectrum management, meant as identification, coordination, and satisfaction of requirements, can help in solving these problems.

The paper discusses major aspects of spectrum management and gives basic information about its international aspects. General sharing problems are discussed in Section 2, and spectrum management issues in Section 3. Section 4 describes concepts of frequency allocations and frequency assignments. Section 5 introduces spectrum engineering and monitoring. Section 6 contains concluding remarks. The last section lists 23 references for further reading.

2. RESOURCE SHARING

2.1. Pasture Model

Common resources have one disadvantage which can be explained best on an example of a pasture open to all. Because the pasture is free of charge, it is to be expected that each herdsman try to maintain as many cattle on it as possible. Such an arrangement works well until the number of beast reaches the carrying capacity of the land. At this point, as described by Hardin [13], the inherent logic of the commons proceeds as follows: "As a rational being, each herdsman seeks to maximize his gain. Explicitly or implicitly, more

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* Note: The views expressed in this paper are those of the author and do not necessarily reflect those of CCIR or ITU.

or less consciously, he asks 'What is the utility to me of adding one more animal to my herd?' This utility has one negative and one positive component:

1) The positive component is a function of the increment of one animal. Since the herdsman receives all the proceeds from the sale of the additional animal, the positive utility is nearly +1.

2) The negative component is a function of the additional overgrazing created by one more animal. Since, however, the effects of overgrazing are shared by all herdsmen, the negative utility for any particular decision-making herdsman is only a fraction of -1.

Adding together the component partial utilities, the rational herdsman concludes that the only sensible course for him to pursue is to add another animal to his herd. And another; and another... But this is the conclusion reached by each and every rational herdsman sharing a commons. Therein is a tragedy. Each man is locked into a system that compels him to increase his herd without limit - in a world that is limited. Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in the freedom of the commons."

Is this applicable to the radio frequency spectrum? The pasture and the spectrum are quite different objects, but there are some analogies. Indeed, the spectrum cannot be fenced. It goes free of charge at international conferences. It has limited carrying capacity. A portion of spectrum used by one radio system is denied to others. The main conclusion from the pasture model is that the complete freedom in use of a common resource may work satisfactorily only under conditions of low-population density, when interference between the users of the resource are negligible. As the population grows, mutual interference appear, and the concept of its free use has to be abandoned.

Our past confirms that the approach to common resources changes. Firstly, the commons in food gathering were abandoned. Farmland has been enclosed, and there is no free farmland now. Later, open pastures and hunting and fishing areas have been restricted. Then, using the commons as a place for waste disposal has been abandoned and restrictions on the disposal of sewage are now widely accepted throughout the world. Finally, a concept of environmental protection was developed, and restrictions have been imposed in many countries on the pollution of land, water, air, and electromagnetic environment. The issue of rational use of resources has become an essential element, both on national and world-wide scales.

When considering the future of limited resources, one can indicate several general approaches [13]: "We might sell them off as private property. We might keep them as public property, but allocate the right to enter them. The allocation might be on the basis of wealth, by the use of an auction system. It might be on the basis of merit, as defined by some agreed-upon standards. It might be by lottery. Or it might be on a first-come, first-served basis". Any of these options implies an organizational framework required for negotiations, coordinations and consultations among interested parties, as well as for verification of compliance with agreements.

2.2. Preferences

Which of the approaches to the sharing a common resource is the best one? Each of them can be questionable and objectionable, dependent on the criteria applied, and the final answer results from human hierarchies of values. Although discussion of non-technical issues is beyond the scope of this paper, one must realize that it is often impossible to separate technical aspects of resource sharing from their economical, social, legal, and political contexts, and from the interests affected by them. The sharing problem cannot be solved by technical means only, without involving systems of human values and ideas. Firey [9] points out a significant role of tradition: "Every adoptable set of resource process will be one which is valued by some population in terms of that population's own system of [values]. Where

a resource process involves beliefs and techniques that are incongruous with a people's system of activities, it will not be adopted by that people, however superior it may be by other criteria."

In a pluralistic society the goals and hierarchies of values are often inconsistent and conflicting [2]. Different individuals and groups have different goals and preferences which are partially in conflict with those of other groups and individuals. Furthermore, the capacities of different groups to implement their preferences are widely different. Inconsistency means that progress toward realization of one value or goal is destructive of another value or goal held by the same individual or group. "Conflicting" goals or values mean such goals or values of two groups that cannot be served by the same policies: what enhances one will degrade the other.

2.3. Sharing the Spectrum

It was at the turn-out of the century that a competition in radio communication has been initiated, and soon the population of radio equipment reached a threshold at which mutual interference begun to limit further developments. After a first period of anarchy, major parties interested came to the conclusion that mutual coordination of technical and operational issues in radio communication is beneficial to all. The global nature of the problem required international cooperation. Indeed, only two years after the first transatlantic wireless communication had astonished the world, the first international conference was called to coordinate the use of the radio frequency spectrum. It was the Preliminary Radio Conference Berlin, 1903. At that time the International Telegraph Union, founded in 1865 in Paris, was not yet involved in wireless telecommunications.

The first Radio Conference held three years later, also in Berlin, agreed upon the basic principles of radio spectrum use. A major step at the conference was, among others, the approval of the first Convention and Radio Regulations, and establishment of the International Bureau in Bern. The operating frequencies and other relevant details of radio stations were to be sent to that bureau which became a center of information about the actual use of the radio frequency spectrum, worldwide. In 1927, the Washington International Radio Conference introduced the first Frequency Allocation Table, and created the International Radio Consultative Committee, CCIR. In 1932, in Madrid, the separate conventions relating to radio, telephone and telegraph have been combined into one International Telecommunication Convention, and the name of the Union has been modified to read: "International Telecommunication Union". In 1947, the Atlantic City Conference created the International Frequency Registration Board (IFRB) in place of the Bern Bureau, and set up the present structure of the Union.

3. SPECTRUM MANAGEMENT

3.1. Basic Rules

It is commonly accepted that the usage of the spectrum must be controlled by various legal, administrative, technical, and operational measures, both on national and international scales, in order to assure satisfactory operation of radio systems. Licensing i.e. formal authorization to use a specified portion of radio spectrum under specified conditions is the most familiar national administrative measure. As the radio wave propagation is not limited to national boundaries, the national and international spectrum management are closely inter-related. Both of them are based on few principles established at the first radio conferences and developed at further conferences. These principles are as follows:

1) the spectrum/orbit resource is free of charge and all countries have equitable access to it;
2) its use is negotiated among interested parties, and their consensus is required;

3) its use is ruled by the principle of electromagnetic compatibility

4) its management is based on the principle of allocation, administrative regulation, central registration, and multilateral coordination in the framework of the ITU;

The electromagnetic compatibility (EMC) is the ability of a device or system to function satisfactorily in its electromagnetic environment without causing intolerable disturbance to that environment [19].

3.2. ITU

The world-wide use of the radio frequency spectrum is coordinated within the organizational framework of the International Telecommunication Union (ITU), the specialized agency of the United Nations for telecommunications with headquarters in Geneva. The purposes of the Union are defined in the Convention ([14], Preamble): "While fully recognizing the sovereign rights of each country to regulate its telecommunications, [...] the plenipotentiaries of the Contracting Governments [...] have agreed to establish this Convention [...] with the object of facilitating peaceful relations, international cooperation, and economic and social development... "

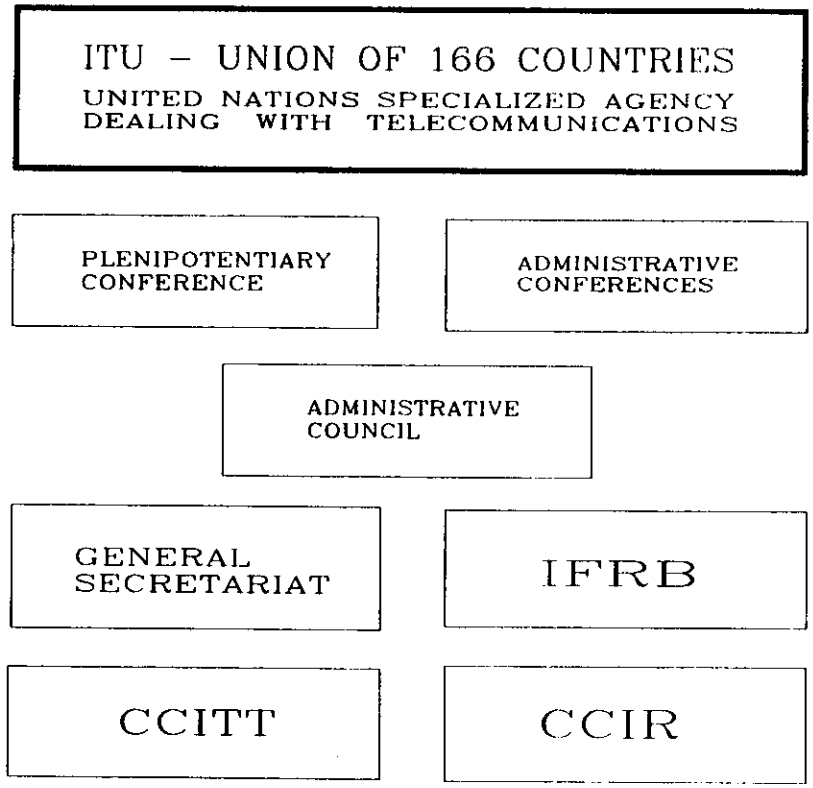
The ITU Members, now totalling more than 160 countries, agreed that the Union shall, among others, effect allocation of the radio frequency spectrum and registration of radio frequency assignments in order to avoid harmful interference between radio stations of different countries. They also agreed that the Union shall coordinate efforts to eliminate such interference and to improve the use made of the radio spectrum. Moreover, they obliged themselves to limit the number of frequencies and the spectrum space used to the minimum and to apply the latest technical advances as soon as possible." ([14], Art. 4-18, 19, 33).

The Members of the Union meet, at intervals of normally about five years, at a Plenipotentiary Conference. This is the supreme authority which lays down the general policy of the ITU, reviews the Union's work and revises the Convention itself, if it considers this necessary. It also establishes the calendar of all ITU conferences and sets a limit on expenditure until the next plenipotentiary conference. The last such a conference was held in Nairobi 1982, and the next one is scheduled for 1989. The spectrum/orbit resource management is only a part of the activities of the Union. Although the whole Union is involved, the following ITU organs assume the primary responsibilities for the issue: the Administrative Radio Conferences, the International Frequency Registration Board (IFRB), and the International Radio Consultative Committee (CCIR).

3.3. Radio Conferences

Further to the tradition, the use of the radio frequency spectrum is based on allocations of frequencies by geographical regions and service categories as agreed by the Members of ITU at Radio Conferences, called "Administrative". These may be world-wide or regional, general or specialized. They may establish and revise Radio Regulations which contain all technical standards and operational rules and procedures relevant to the spectrum use, including frequency allocations. The Radio Regulations complement the International Telecommunication Convention and have the same authority and the same legal force as the Convention.

Since 1947, when ITU joined the United Nations System, there were two general world administrative radio conferences (WARC), one in 1959, and the other in 1979, and several specialized and/or regional conferences. The general WARCs were authorized to deal with virtually all aspects of spectrum use. The specialized WARCs dealt with particular services and/or particular portions of the spectrum. The regional conferences are called to solve specific problems within particular geographic regions. As known, there are three ITU regions: Region 1 which consists of Europe, Africa and part of Asia (USSR and



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Mongolia), Region 2, containing both Americas, and Region 3, consisting of Australia, Oceania, and the remainder of Asia.

3.4. IFRB

The International Frequency Registration Board (IFRB) consists of five independent radio experts, all from different regions of the world, elected by the Plenipotentiary Conference and assisted by a specialized secretariat. They serve as "custodians of an international public trust". They decide whether radio frequencies which countries assign to their stations are in accordance with the Convention and Radio Regulations, and will not cause harmful interference to other stations. Each decision requires a detailed examination of technical and operational parameters of all stations involved. An average of more than 1200 frequency assignment notices arrive at IFRB each week for such an examination, and that number increases each year. If the Board's finding in a particular case is favourable, the frequency is recorded in the Master International Register kept by the IFRB, and thus obtains international recognition. (Not all assignments are submitted to IFRB, see section 4.1).

Among the other major tasks of the IFRB are: participation at the request of governments in the obligatory inter-governmental coordination of the use of frequencies involving space techniques (prior to their notification for recording in the Master Register), the recording of the positions assigned by countries to geostationary satellites with a view to ensuring formal international recognition thereof, and the technical preparation of Radio Conferences.

3.5. CCIR

The International Radio Consultative Committee CCIR is the permanent organ of the Union responsible for studies of technical and operational questions relating specifically to radio communications without limit of frequency range, and to issue recommendations on

them. The objectives of the CCIR are in particular: (1) to provide the technical bases for use by Administrative Radio Conferences; (2) to recommend performance standards for radio systems and technical arrangements which assure their effective and compatible inter-working in international telecommunications; (3) to collect, exchange, analyze and disseminate technical information relevant to the development, planning, and operation of radio systems, including any necessary special measures to facilitate the use of such information in developing countries.

All Member countries of the Union are also members of right of the CCIR. Scientific and international organizations, operating agencies and manufacturers, may also join CCIR work under some conditions. Every few years, the CCIR holds its Plenary Assembly which draws up a list of "Questions" i.e. technical problems the study of which is considered necessary for further development and operation of radio communication services. Among the issues presently under study, one can mention direct satellite broadcasting, high definition television, microwave and broad band ISDN, or global distress and safety systems. More than half of CCIR work concerns compatible use of the radio frequency spectrum and geostationary satellite orbit. The Questions are entrusted to Study Groups composed of experts from different countries. About 2500 experts participated in Study Groups meetings during the recent study period. The studies, theoretical and experimental, are performed on a voluntary basis in laboratories of individual Member countries, and their contributions constitute the basis for the work of Study Groups.

The results of these studies are published as Recommendations, Reports, and Handbooks. Before publication, the draft Recommendations are submitted for approval by the Plenary Assembly. There are about 300 Recommendations and 600 Reports of the CCIR in force covering almost all branches of radio communications. Although not binding, the Recommendations are accepted as world-wide standards. Many of them are referred to or form the basis of the Radio Regulations. Others are applied by Radio Conferences which regulate the use of frequency bands and the geostationary orbit. Because of their great impact, CCIR text are prepared with great prudence. As a consequence, a CCIR Recommendation represents the best solution available, if the issue is not controversial. If the subject is controversial, the Recommendation represents the best compromise achievable. If no compromise can be reach, only CCIR Report can be concurred instead of recommendation.

The foundation of the CCIR created a historical precedent in the world-wide management of the spectrum resource because of the role of technical experts. Instead of functioning as diplomats, whose major preoccupation is "balancing of political interests" between sovereign states, their prime concern has been to achieve constructive cooperation in the utilization of technology to best exploit the resource [10].

4. FREQUENCY ALLOCATIONS & ASSIGNMENTS

The use of the radio frequency spectrum has been based on frequency allocation principles, which differentiate between geographical regions and service categories. The basic rules agreed upon by the ITU Members are published in the Radio Regulations (Table of Frequency Allocations). "Allocation" means the distribution of a frequency band to a service, "allotment" - to a country or area, and "assignment" - to an individual radio station.

Some allocations are world-wide, i.e. identical throughout the world. In other cases allocations are regional, i.e. uniform throughout a particular region. In still other cases there are allocations specific for a single country, or a group of countries, in addition to, or different from, allocations approved by a majority of ITU Members (so-called "footnotes" to the Table of Frequency Allocations). Frequencies allocated to a service are available for use by

any country, subject only to the limitations contained in the Radio Regulations.

4.1. Dual Approach

A country can make an assignment to an individual station, or an assignment plan to a whole network of its stations. If that use could cause interference outside the territory of the country, or if it is intended for international communication, or if the assigning country seeks an international recognition for its assignment, it has to notify the IFRB and seek registration in the international list of frequency assignments and geostationary orbit positions. Each frequency and orbit assignment notified to IFRB is examined not only for its conformity with the Radio Regulations but also for its compatibility with other, already registered, frequency assignments and plans. If the result of examination is favourable, the assignment is registered, if not - it is returned for modification as appropriate. An advice concerning selection of proper frequency is given by IFRB, if needed.

This is so-called "ad hoc" frequency distribution method. There is one exception to that rule: there are certain services which are subject to so called "a priori" frequency plans. In "a priori" frequency plans specific bands allocated to specific services (or positions on the geostationary satellite orbit) are parcelled among individual countries well in advance of their real use. Individual regions may have various allotment plans for specific services e.g. broadcasting, within their respective areas. "A priori" plans make a one-time distribution of the resource on the basis of present needs and predicted future requirements of the parties interested.

For services subject to "a priori" planning, a frequency assignment in accordance with the plan receives protection from any other assignment. In the case of "ad-hoc" managed services, the protection is given in accordance with priority of registration dates - a system sometimes described as "first-come, first-served". In addition to that, three service categories are differentiated: primary, permitted, and secondary. Primary and permitted services have equal rights, except when planning, stations of a primary service have priority in choice of frequencies. Stations of a secondary service should neither cause interference to, nor claim protection against interference from, stations of primary and permitted services.

4.2. Strong & Weak Points

Advocates of the "a priori" approach indicate that the "ad hoc" method is not fair because it transfer all the burden of coordination to the latecomers which must accommodate their requirements to the existing uses of the resource. Replacement of "ad hoc" methods by systematic plans allows for the "fair" sharing the resource and for its rational use, they say.

Opponents, on the other hand, point out that "a priori" planning approach freezes technological progress and is unrealistic because it is impossible to predict future requirements with a needed degree of accuracy. Plans based on un-realistic data are of no practical value. In addition, as the radio spectrum is available at no cost, there is no mechanism to limit the requirements. Although the Convention calls for minimizing the use of the spectrum/orbit resource, each country - as pointed out by Robinson [18] - has an incentive to overstate its requirements, and there are few accepted or objective criteria for evaluating each country's stated need. In fact, the individual country itself may have only a vague perception of its needs over the time period for which the plan is to be constructed. Under these circumstances, it is easy to make a case that plans are not only difficult to construct, but when constructed will lead to a waste of resources, as frequencies and orbit positions are "warehoused" to meet future, indeterminate needs. One of the main advantages of the "ad-hoc" spectrum distribution is that it automatically eliminates the "warehousing" problem, according to its advocates.

5. SPECTRUM ENGINEERING

Scientific and engineering elements of spectrum management are known as "spectrum engineering" [15]. One of the basic problems of spectrum engineering was to define a measure of "spectrum use" [1]. A "used" portion of the spectrum/orbit resource means "denied to others". Traditionally, radio transmitters have been considered the users of the spectrum resource. They use it by radiating radio power - so much power that receivers of other systems cannot operate in certain locations, times, and frequencies because of unacceptable interference. Notice that the transmitter denies the space to receivers only; in no way it prevents another transmitter from emitting power into the same location. Receivers use the spectrum space because they deny it to transmitters which may cause harmful interference. Efficient use of the spectrum is achieved by (among other things) the isolation of radio systems obtained from antenna directivity, geographical and frequency spacing, and time division. Therefore, the measure of spectrum utilization is defined to be the product of frequency bandwidth, the geometric (geographic) space and the time denied to other potential users.

In this connection we have to distinguish between the physical and administrative denials [1]. The space physically (or actually) denied depends on numerous processes and parameters which can be only roughly estimated. Thus, in order to simplify spectrum management, the administrative denial is used in organizational processing as a practical approximation to physical denial. Consequently, the space is administratively denied by spectrum management rules even if it is really not physically denied. One of the means to improve the use of the spectrum resource consist, therefore, in making (1) more precise estimations for physical denials, and (2) better approximations of administrative denials to physical denial. To do that, however, further progress in spectrum engineering and generally in radio sciences seems to be needed. Adequate propagation prediction methods are of special importance here.

5.1. Monitoring

One of major elements of spectrum engineering is monitoring. Its task is to identify the actual use of the spectrum, and to check the compliance with agreements, standards, rules and regulations, as well as to solve radio-interference problems. The monitoring of radio spectrum consists of observing and overseeing the electromagnetic environment under the actual traffic conditions. Monitoring measurements are remote measurements of spectrum occupancy and emission parameters, and include identification and localization of interference sources. By acceding to the International Telecommunication Convention, each Administration not only accepts all restrictions and limitations imposed by the Radio Regulations, but also agrees to continue appropriate monitoring activities and to cooperate in the development of the international monitoring system.

5.2. Optimization

There are millions of radio systems around the world, interconnected by means of electromagnetic fields. They operation would dissolve into chaos without a proper coordination of their operation in space, time and frequency. Their appropriate operating frequencies, times, and powers, their antenna locations, heights, polarizations and patterns, their signal structures and signal processing methods, as well as protection criteria have to be adequately determined, within budget, technology, and other constraints.

The spectrum management problem is a special case of a more general problem, which can be formulated as follows: given a collection of consumers who place demands upon a set of resources, find an assignment of consumers to resources that (1) satisfies

various constraints and (2) minimizes (or in some cases maximizes) a given objective function [12]. However, the identification of proper variables, the objective function, and relevant constraints is not a simple task. Moreover, the usual problem in optimization procedures is with the time or work required to find the solution, and sometimes, the exhaustive inspection of all possibilities is the only exact method available. Due to complex interactions and an enormous amount of variables involved, attempts to apply rigorous formal methods to real-life situations usually lead to "intractable" problems [20]. Consequently, various approximate and heuristic methods have to be applied [12, 21]. Despite all efforts made, frequency management is still not yet fully based on stringent scientific and technical criteria [22]. It seems, however, that some techniques and approaches developed in other areas, such as operation research, graph theory, game theory, and computer simulation techniques could find applications in spectrum management problems, still waiting for efficient solutions.

6. CONCLUDING REMARKS

The disproportion between the demand for the spectrum/orbit resource on one hand, and its available capacity on the other hand, calls for improvement of the existing resource management practices. The present administrative allotment concept and "service separation" philosophy were elaborated several years ago. In the meantime, the population of radio stations increased enormously and new radio technologies have been introduced. Digital signal processing, microelectronics, and computer techniques opened new horizons. Also the political situation over the world has changed dramatically, and many new countries which have got independence seek their share of the common resource.

To follow these changes, proposals are published from time to time that the existing administrative regulation system should be replaced by a competitive market economy mechanism. Such a deregulation is urged as a means of allowing market forces to distribute spectrum/orbit equitably to the market sectors where demand is greatest. Advocates of this idea indicate that it match the demand to the available resource capacity. Moreover, according to some opinions, relying upon administrative decision-making is inferior to relying on market forces because decisions are arbitrary and often mistaken in determining what is the best interest of users [8, 23]. In addition, the Radio Regulations, modified many times by successive administrative conferences, became very complex and difficult not only to implement but also to understand.

One expected that WARC'79, the largest general conference in the history of the ITU, would be a major vehicle for debating a new order of the spectrum/orbit use. In reality WARC'79 did not established any new principles, and it was rather to adjust existing regulations governing spectrum allocations and use to accommodate new and future requirements. The debate on general principles was left essentially untouched by the WARC [18].

How radio communication activities can be developed to the advantage of all nations, raises global implications. Although the necessity of international coordination in the spectrum use is generally understood, it is not always clear whether the coordination is desired in order to resolve conflicts where parties adhere to their own individual objectives, or in order to achieve certain common, collectively agreed goals.

Spectrum/orbit sharing, world-wide, requires every nation to study the best ways of the use of the resource, as well as to study the nations' needs and elaborate an adequate position and effective interface for negotiations in the international framework. The technical elements of that process are more and more very important and deserving the most competent attention. It seems that many problems encountered in the present use of the radio spectrum and

geostationary orbit are symptoms of inadequacies in our knowledge, and that further scientific efforts can offer practical solutions. The specific role of science has been best described by Gvishiani [11]: "By its very nature, science is well equipped for internationally coordinated efforts directed to the solution of common problems. Science is universal, independent of nationality, ideological convictions or political orientation, which makes joint efforts much easier than in any other field". As the time between scientific discovery and its application becomes shorter and shorter, it is more and more difficult to separate the pure and applied aspects of disciplines, and the need for close collaboration between scientists and engineers becomes essential more then ever.

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