## 2.1 History of the International Reference Ionosphere

*K. Rawer*
*Herrenstr. 43, 7806 March*
*Federal Republic of Germany*

*L. Bossy*
*Université Catolique de Louvain*
*174, avenue W. Churchill, 1180 Bruxelles*
*Belgium*

Radio-observations of the very first satellites yielded some very important results concerning the upper atmosphere. Orbital period determinations via radio-location showed that temperature and density variations in the upper atmosphere are much greater than expected. Therefore, the newly-founded Committee on Space Research (COSPAR) decided that a set of empirically based tables describing these findings should be established. This task was considered of such high importance that a commission of specialists was established to carry it out. This group in 1961 presented its findings under the name of COSPAR International Reference Atmosphere (CIRA). The collection was widely used by the scientific community. Taking account of the increasing amount of measured data followed up by an increasing number of theoretical approaches, the continuous work of the CIRA Task Group culminated in the release of three more CIRAs in 1965, 1972, and 1986.

Realizing the success of CIRA, S. Bowhill proposed a few years later to establish a comparable reference for the ionized constituents of the atmosphere, to be called International Reference Ionosphere. According to the original terms of reference, it should contain empirically based tables describing monthly median vertical profiles of the main parameters of the ionospheric plasma. Like CIRA, IRI should be usable as a standard reference for the design of experiments, the estimation of environmental and other effects, for checking theories, etc. The profiles should be provided for suitably chosen locations, hours, seasons, and levels of solar activity. In contrast to theoretical models, the IRI should combine approved experimental results so as to be a useful reference with no dependence on theoretical assumptions.

To take care of this new task, COSPAR in 1968 established the "Task Group on IRI" and nominated K. Rawer for chairman. This group was given the task of promoting and coordinating the international efforts toward the goal described in the above terms of reference. In 1969, the International Union of Radio Science (URSI) decided to concur with COSPAR in the project. A preliminary set of tables (for two locations, noon and midnight, three seasons, and two levels of solar activity) was presented as an example to the URSI General Assembly 1975 in Lima, Peru.

The Task Group made two decisions at the very beginning of its work:

(1) Since most users have access to computer facilities, the results should be presented as a computer code rather than as a set of printed tables. Tables and figures could then be produced with this code.

(2) The peak of the ionosphere should not be modeled independently but should be determined by an existing computer code published in 1967 by the Comite Consultatif International des Radiocommunications (CCIR).

The CCIR code is based on a large set of measurements made by ionosonde technique at more than a hundred stations worldwide. This data base, however, contains large gaps over the oceans. In order to fill these gaps, Jones and Gallet (1965) had introduced a particular, coordinate-dependent, interpolation system that was bound to geographic coordinates. To give a more coherent picture, the CCIR version applies another, special latitudinal coordinate (MODIP) that was proposed by Rawer (1963).

The terms of reference asked for four parameters to be represented in IRI, namely, electron density, electron and ion temperature, and (positive) ion densities. In order to reach consistency with the independently obtained electron densities, the ion densities should be given as relative, not absolute, values. Consistency was also asked for between the plasma temperatures and the CIRA neutral temperature.

As a general philosophy a data set, before being introduced into the system, had to be critically evaluated by the experts. Comparing results of different techniques was one way of checking data reliability, a powerful one as was found out. In fact, critical comparison of different measuring methods turned out to become a major IRI task. For example, a special meeting on "Methods of Measurements and Results of Lower Ionosphere Structures" was initiated by the group and was held in 1973 at Konstanz, Federal Republic of Germany. With the guidelines established during the meeting in mind and in broad international cooperation, a great effort was started to gather relevant data from different techniques.

At the onset of IRI work, it had been expected that the amount of accessible and reliable data would be rather large for electron densities, much smaller for temperatures, and rather poor for ion composition. In general, this was found to be the case. However, even the electron density profile data showed rather important and unexpected gaps. In spite of the existence of an enormous amount of evaluated ionogram parameters, true height profiles were only available for a small number of stations providing by no means a worldwide coverage. The inversion technique, needed to obtain true height profiles, had been applied only at very few places at temperate latitude. Even there, some uncertainty remained because of the E-F-valley problem (Gulyaeva et al., 1990). Several stations run by U.S. institutions had produced so-called "composite profiles" obtained with an artificial "median ionogram" (established month by month and hour by hour). Though the reliability of these results might be questionable, they were the only available input at lower latitudes. Also, the polar caps were de facto excluded because of the lack of specific information and because of the great variability encountered in this region. It was felt that under the extreme conditions in the polar caps the CCIR maps, which are based on monthly median station data, are unable to produce a representative picture.

As for the topside, mainly two sources of information were available at the time, namely, incoherent scatter observations (unfortunately at few stations only) and topside sounder profiles. In situ measured plasma densities could be used only for checking purposes. A very large number of topside ionograms taken by the two Alouette satellites had been inverted to density profiles. Unfortunately, an inquiry showed that these were incomplete because the peak electron density value was regularly missing. Thus, regrettably, the many profiles in the archives were not usable for the IRI purpose. Later Bent and Llewellyn (1973) established an empirical model description based mainly on about 10,000 topside ionograms obtained by Alouette above North and South America. While the influences of solar activity and F-peak density are given by simple formulas in this model, the latitudinal variation is described discontinuously considering only three geographic ranges. S. K. Ramakrishnan produced a continuous description for the Llewellyn and Bent (1973) model. There remained, however, serious problems in the region around the geomagnetic equator where the original description does not admit an explicit dependence on latitude (Bilitza, 1985a, 1986).

For the height of the F2-peak, *hmF2*, reliable data are obtained by the incoherent scatter technique; however, only a rather small number of stations operate worldwide. Fortunately, in view of propagational applications, ionosonde stations had regularly determined a parameter, *M(3000)F2*, which has some relation with *hmF2*. A large and worldwide thesaurus for this parameter was readily available in the form of the CCIR numerical maps similar to the CCIR peak density maps. From a compilation of ionogram data (under some simplifying assumptions) Shimazaki (1955) had found a linear relationship between the peak height *hmF2* and *M(3000)F2*, a relationship that was later improved by different authors (Bradley and Dudeney, 1973; Bilitza et al., 1979). The improved formulas take account of additional parameters which influence the *hmF2-M(3000)F2* relationship, in particular refraction in the E-region. With such relations the *M(3000)F2* maps could be transformed into *hmF2* maps. The results obtained by incoherent scatter had been taken into account for the improvement introduced by Bilitza et al. (1979).

Particular problems were encountered in comparisons of measurements in the lowest ionosphere (below 100 km) that had been obtained with different techniques. The data were so widely different that a special symposium was held (see above) in order to reach an agreement about general guidelines (Rawer, 1974). It was stated that in situ measurements, when combined with radio propagation measurements between ground and rocket, would be used as the primary input. A compilation of acceptable D-region rocket data was made by Mechtly and Bilitza (1974). For the nighttime lower E-region and valley two differing compilations were available from Maeda (1969, 1970, 1971, 1972) and Soboleva (1972, 1973). Comparing both with Schumann resonances, H. G. Booker gave a strong vote in favor of the Maeda model.

The full (vertical) profile of plasma density was described by a set of mathematical expressions, each valid in a certain height range. This rather complex system allowed a correct representation of the most important inputs, like the peak densities of the main layers. On the other hand, it was not well suited for "full wave" computations. For such computations (at extremely low frequencies), Booker (1977) proposed the use of fully analytic functions of a type that P. S. Epstein had defined in the thirties. His proposal was, in fact, used in the topside description but for good reasons could not be realized for the full profile at that time.

At least by day the electron temperature can be much higher than that of the ions, the latter being also less variable. Ion temperature data observed with the retarding potential analyzer technique by Dumbs et al. (1979) were accepted as reliable inputs together with ground-based measurements made at a few places by the incoherent scatter technique. The in situ results were used to derive the latitudinal variation between the incoherent scatter stations. The difference to the lower CIRA neutral temperature values becomes quite appreciable above 400 km. Near the 100 km level agreement of both temperatures (as requested by COSPAR) was arranged for within the ion temperature formula.

The same data sources were used for the electron temperatures. The latitudinal variation was mainly taken from a compilation of data measured aboard the AEROS satellites (Spenner and Plugge, 1979). Later Bilitza et al. (1985) improved the temperature model by introducing Langmuir probe data compiled by Brace and Theis (1981) from the AE-C and ISIS 1 and 2 satellite missions. It is well documented that the electron temperature and density are closely anti-correlated in the daytime ionosphere (e.g., Bilitza, 1975; Brace and Theis, 1978). Therefore, in the formulas used at first, the electron temperature was coupled with the actual electron density. Later it was found that for monthly medians a correlation between the temperature and density profile was not meaningful. Density and temperature profiles were, therefore, established independently from the relevant monthly median data. In case, however, actual density profiles for a specific time and location are at hand, it is recommended to apply a correction to the median temperature profile via an empirical (inverse) relation specified in IRI (Bilitza et al., 1985).

The data base for (positive) ion composition was rather poor at the time. Most of the published rocket or satellite data had been given as absolute densities and did not provide the total plasma density needed to determine the relative ion composition. Further, a large set of simultaneous measurements with mass spectrometers and a retarding potential analyzer (RPA) aboard the AEROS satellites had shown that while the spectral resolution is much better with mass spectrometers, the intensity indications are less reliable with the more involved spectrometer systems than with the simpler retarding potential method. The RPA data could be reasonably well evaluated in three groups: (1) hydrogen and helium ions, (2) oxygen and nitrogen (atomic) ions, and (3) the group of molecular ions: $O_2^+$, $N_2^+$, and $NO^+$. Satellite RPA measurements (Dumbs et al., 1979) were used for the model at heights above 220 km. A few ion mass spectrometer (IMS) data (Taylor, 1972) were also considered in building the model. Between 100 km and 250 km the model relies on rocket IMS data compiled by Danilov and Semenov (1978), including American, Russian, and a few European measurements.

The most difficult range to describe is below 100 km. Positive cluster ions appear below about 92 km and are the most abundant species below about 84 km. There were only three groups in the world that had developed techniques (with cooled spectrometers) as needed at heights at which collisions play an important role. It was not possible to establish a profile in agreement with all observations because cluster ions are often destroyed in the spectrometer itself (by the electric fields that are applied in the measuring system). After some discussion, data obtained with a particularly designed instrument (Kopp et al., 1978; Kopp, 1984) were taken as reference. Only the total sum of all clusters was given since the number of individual species is large and transitions between species is frequent.

A similar situation was encountered with negative ions that occur only at altitudes below about 80 km. These are also clusters. Only one group had made measurements in this difficult height range (Arnold et al., 1971). Their average daytime profile was incorporated into IRI.

After the first IRI was released in 1978 (Rawer et al., 1978a), it was critically tested with a wide variety of data. This testing period lasted about one decade. Since 1982, COSPAR in cooperation with URSI has organized yearly workshop meetings to discuss and improve the model (see Table 1). The computer code has been changed step by step and new features introduced as they have become available. COSPAR has published the papers presented at these meetings in its periodical, *Advances in Space Research.* The proceedings of seven of these workshops have appeared in the years from 1982 through 1990 (see Table 1). More than 300 scientists are listed as authors of more than 230 individual papers filling a total of 1,458 pages. The tables of contents of these reports are listed in Chapter 5.

Another result of these discussions is worth noting: For quite a number of unresolved questions, the existing data base was insufficient to give a well founded answer. As a reaction, special data analysis and collection efforts were undertaken in different countries. For example, the AEROS satellite team decided to organize the data reduction and evaluation scheme in such a way that a worldwide picture of electron and ion temperatures, and ion

**Table 1: Workshop Meetings for Discussion of IRI**

| Year | Place | Published Year | Published Papers | Publication | Pages |
|---|---|---|---|---|---|
| 1971 | Seattle (USA) | 1972 | 21 | *Space Res.* XII | 1229-1335 |
| 1973 | Konstanz (FRG) | 1974 | 52 | See Rawer (1974) | 1-460 |
| 1974 | Sao Paulo (Brazil) | 1975 | 5 | *Space Res.* XV | 295-334 |
| 1982 | Ottawa (Canada) | 1982 | 14 | *Adv. in Space Res.* 2, # 10 | 181-257 |
| 1983 | Stara Zagora (Bulgaria) | 1984 | 24 | *Adv. in Space Res.* 4, # 1 | 1-169 |
| 1984 | Graz (Austria) | 1985 | 18 | *Adv. in Space Res.* 5, # 7 | 1-112 |
| 1985 | Louvain (Belgium) | 1985 | 23 | *Adv. in Space Res.* 5, # 10 | 1-130 |
| 1986 | Toulouse (France) | 1987 | 22 | *Adv. in Space Res.* 7, # 6 | 1-127 |
| 1987 | Novgorod (USSR) | 1988 | 53 | *Adv. in Space Res.* 8, # 4 | 1-251 |
| 1988 | Espoo (Finland) | 1990 | 24 | *Adv. in Space Res.* 10, # 8 | 1-132 |
| 1989 | Abingdon (UK) | 1990 | 17 | *Adv. in Space Res.* 10, #11 | - |

composition could be obtained in a readily usable form. In the U.S.S.R. and in India several rocket campaigns were conducted to get a sound data base for an improved ion composition vs. height formula.

Not all steps taken in the course of discussions were found to be favorable. While originally an interrelationship between electron density and temperature was implemented, it was found that, in spite of clear experimental evidence for individual cases, this is not justified when dealing with monthly medians. Another unfortunate decision (in response to a request by the competent URSI Commission) was made with the temporary introduction of Chiu's (1975) simplified peak description as a second choice besides the numerical CCIR maps. This action was withdrawn later when it became apparent that this (regionally helpful) description is not acceptable in many parts of the world.

In their 1978 paper, Rawer et al. (1978b) noted a few open problems: checking by propagation experiments, comparison of elf propagation with full wave computations using IRI, comparison with ionospheric absorption measurements, extension toward greater heights, improved data base for ion composition, in particular at lower and at very great heights, and improved data base in the low latitude belt. Some of these problems were resolved; meanwhile, others are still pending.