

# Goals and Status of the International Reference Ionosphere<sup>1</sup>

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Under the supervision of an international steering committee, basic data for establishing ionospheric profiles were gathered, critically reviewed, and used for establishing vertical profiles of the most important parameters of the ionosphere, namely, electron density, electron and ion temperature, and (positive) ion composition. The data sources used are described in detail, their reliability and coverage is discussed, and remaining problems are reviewed. The International Reference Ionosphere (1978) is to be published soon by URSI in the form of computer programs.

## GENERAL CONSIDERATIONS

Since 1969, URSI and COSPAR have been working together on the project 'International Reference Ionosphere' (IRI), which is intended to summarize in a condensed form the most important results on the terrestrial ionosphere. Following Ciria, the 'COSPAR International Reference Atmosphere,' the original intent was to prepare a set of profile tables for the main parameters characterizing the ionospheric plasma, namely, electron density, electron and ion temperature, and (positive) ion composition. Like Ciria, the tables would be usable as a standard reference, for example, for the design of experiments, the estimation of environmental and other effects, for checking theories, etc. The profiles would be provided for suitably chosen locations, hours, seasons, and levels of solar activity.

Work on IRI was promoted by an international steering committee, which held sessions at most COSPAR and URSI meetings, and a special joint symposium on the lower ionosphere was held in 1973 at Konstanz [Rawer, 1974].

In contrast to theoretical models the IRI is intended to combine approved experimental results so as to be a useful reference, with no dependence on theoretical assumptions. In the first years of data compilation it was found that experimental results were few or nonexistent for certain parameters and under certain conditions. Therefore the steering committee stimulated additional investigations, in particular of ion composition and of the lower ionosphere. As compared with the neutral atmosphere the enormous variability of ionospheric plasma parameters in time and space presents a serious problem (Figure 1).

After a presentation and discussion of the procedures adopted [Rawer, 1975] a preliminary set of tables for two locations, noon and midnight, three seasons, and two solar activities was presented as a preliminary report to the URSI General Assembly at Lima [Rawer *et al.*, 1975]. Since most users now have computing facilities, computer programs for establishing these tables were also given in the same report. URSI accepted this as a basis for a first edition of IRI, asking for the computer programs only, since with such programs in hand, users can easily print out the tables.

The forthcoming IRI (1978) will therefore only contain an introduction, the necessary computer programs in both Algol

60 and Fortran 4, and data inputs as tables or programs. Geographic interpolation is provided as far as it is considered to be feasible with the present basic data set. It must be emphasized that the available basic data are not adequate to describe all desired conditions. In spite of these shortcomings the steering committee has now decided to publish a first official edition.

Following the wishes of scientists engaged with full-wave computations a typical set of profiles will also be given, in which each individual profile is to be described by a single analytical function covering the whole range of heights. In this kind of presentation the original input data are not directly apparent. The main program, however, is strictly based on measured data inputs and is therefore composed of a set of independent functions, each referring to a particular range of heights. In the following sections the data sources for the different parameters in the present status will be described in more detail.

## PLASMA DENSITY

The key value is the peak electron density, which is reached in the  $F_2$  layer of the ionosphere. The most important data base for this quantity is the international ionosonde network. From hourly measurements at more than 100 stations over a period of more than 20 years the Comité Consultatif International des Radiocommunications (CCIR) has established a computer program which constitutes the best available representation of such data [CCIR, 1967, 1974]. Weak points are the oceans and the southern hemisphere in general, where stations are rather scarce. Since the peak electron density is thus obtained from an independent program, our special programs are only concerned with the relative profile shape (peak density reduced to 1).

The bottomside profiles are mainly based upon ionograms reduced to true height profiles. Since this constitutes a very large correction of the measured virtual heights (see Figure 2), the accuracy of this procedure is limited. It is also limited by horizontal gradients, which occur rather often as a consequence of gravity waves. It is also not feasible to deduce the true profile in the 'valley' between regions  $E$  and  $F$  from ionograms. Fortunately, information for this height range can be obtained from incoherent scatter, particularly from the former station at Malvern, United Kingdom.

Another limitation of density profiles computed from ionograms is the peak height, which can only be obtained by a rather uncertain extrapolation procedure (see Figure 2). Reliable data for this parameter are obtained at the incoherent scatter stations which are considered as primary inputs. How-

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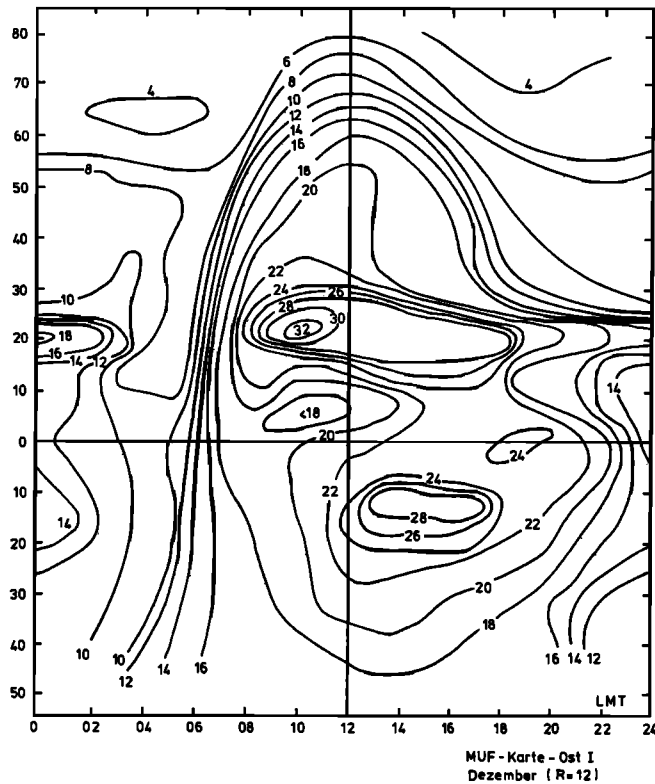


Fig. 1. Map of the ionospheric parameter MUF (3000)F2 as a function of latitude (ordinate) and local time (abscissa). Established from ionogram data around zero longitude for low solar activity, for December.

ever, since these are only routinely available from three latitudes, a combined procedure was developed for deriving the peak height from the parameter  $M(3000)$ , for which abundant data are also summarized in the above mentioned CCIR program. Empirical relations between this parameter and the peak height have been established by different authors [Shimazaki, 1955; Bradley and Dudeney, 1973; Eyfrig, 1974]. We now use a more involved relation developed from matching to the existing incoherent scatter data [Bilitza, 1977].

For the topside profile, mainly two sources of information are available, namely, incoherent scatter observations (unfortunately at few stations only) and topside sounder profiles. For the latter a descriptive compilation exists for the longitude of America in a model established by Bent, which compares favorably with available incoherent scatter evidence. We take the data of Bent's model as input for a new continuous descriptive formula, thus avoiding the subdivision of height ranges of the original mode [Booker, 1977]. Our formula follows the approach indicated in this recent publication. Unfortunately, in situ measurements of satellites are not easily incorporated, since it is rather difficult to deduce vertical profiles from measurements made in an essentially horizontal orbit. It is, however, intended in the future to compare satellite measurements with the present model. Some comparisons were recently made with data from satellite Aeros B [Rawer et al., 1977]. A few examples of electron density profiles obtained with IRI are shown in Figure 3.

The lowest ionosphere at altitudes below 100 km is not well observed by routine sounding. In the literature, profiles for this height range have been deduced with different techniques leading to widely differing results. This problem was discussed

extensively at the 1973 symposium [Rawer, 1974]. It was agreed that in situ measurements which were combined with radio propagation experiments between the ground and the rocket should be taken as the primary input. The results of other ground-to-ground propagation experiments cannot be considered to be suitable because of the inversion procedure needed when determining a profile. A compilation of rocket data for the  $D$  region and lower  $E$  region was made along these lines by Mechtly and Bilitza [1974], who found that a rather well defined characteristic frequency exists for the  $D$  region in daytime (Figure 4).

By using their results a typical profile shape was established, at least for daytime. Since nighttime observations are rather scarce, it is difficult to determine the nighttime profile. In particular, the depth of the valley above the  $E$  regions remains uncertain. Compilations from nighttime rocket soundings were available from Maeda [1969, 1970, 1972] and from Soboleva [1973]. After comparing model calculations and measured data, in particular those on Schumann resonances (H. G. Booker, private communication, 1976), we felt that Maeda's valley shape might be preferable to Soboleva's very deep night valley.

Another difficulty exists at very large heights. IRI (1978) is mainly based upon data measured up to 1000 km, but some profiles can be extrapolated up to 2000 km with the same equations. For altitudes above this limit a subgroup was established under M. Rycroft, which is now at work to combine evidence from in situ measurement, whistler observations, and probably also propagation experiments toward space vehicles.

#### TEMPERATURE OF ELECTRONS AND IONS

Heating of the upper atmosphere stems mainly from the excess energy set free by photo-ionization. A population of 'hot' photoelectrons is thus formed, which can readily heat the

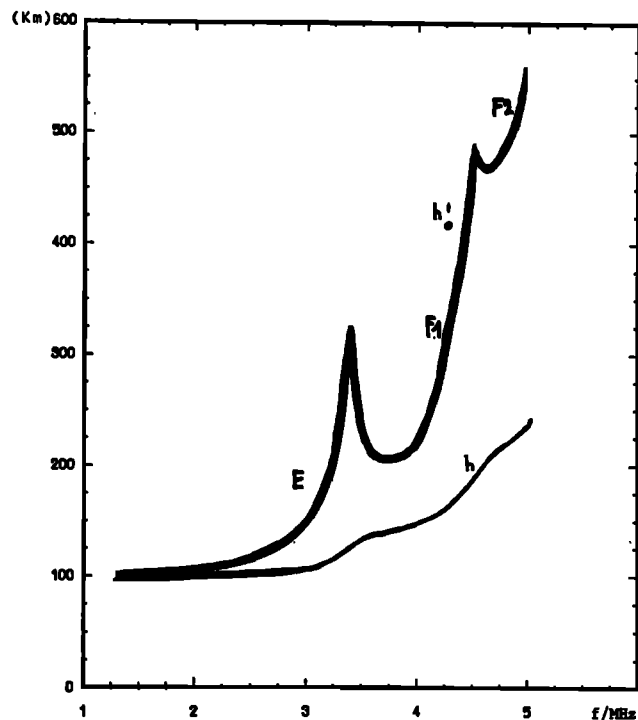


Fig. 2. Ionogram trace (heavy curve), giving virtual sounding altitude versus sounding frequency, and corresponding 'true height profile' of height versus plasma frequency.

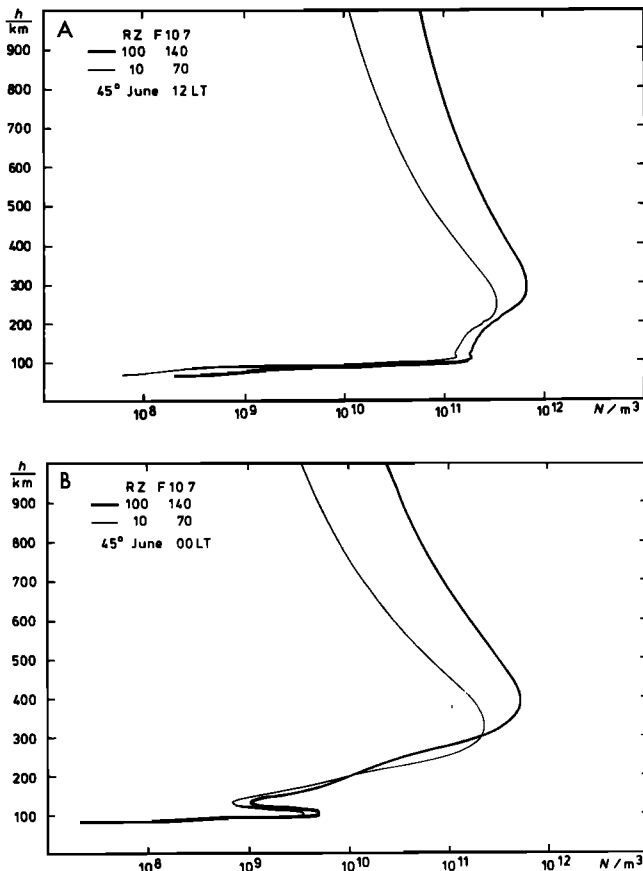


Fig. 3. IRI (1977) electron density profiles for mid-latitude, for June. The heavy curve is for high solar activity, and the light curve for low solar activity (a) at local noon and (b) at midnight.

large number of thermal electrons, thereby raising the electron temperature. Similarly, corpuscular heating goes mainly into heating the ambient electron population. The heat contact between ions and neutrals is very strong in the E region but decreases at greater altitudes. Since Coulomb collisions have a much larger cross section than neutral collisions, the heat contact of ions with electrons eventually becomes better than that with neutrals, so that the ion temperature is raised above the neutral temperature by heat given to the ions by the electrons. The result is that in the F region and above, the electron temperature is higher than the ion temperature, which itself may be higher than the neutral temperature. Also, since the heat capacity of the electrons is quite small in comparison with that of the ions or of the neutrals, the electron temperature may undergo larger variations which represent only small changes of heat input or loss. Quite often, variations of the electron temperature result from variations of the heat lost to the ions, which increases with the square of the plasma density. The electron temperature is therefore a rather variable quantity and one that is difficult to model accurately.

The ion temperature is measured with good precision by the incoherent scatter technique. The observations show that the difference between the ion temperature and the neutral temperature becomes appreciable above 400 km (see Figure 5). There are now also ion temperature values from in situ measurements by satellites with the retarding potential analyzer technique [Hanson et al., 1970; Dumbs et al., 1977]. Some of these data were used to determine a latitude variation between the profiles measured at the incoherent scatter stations.

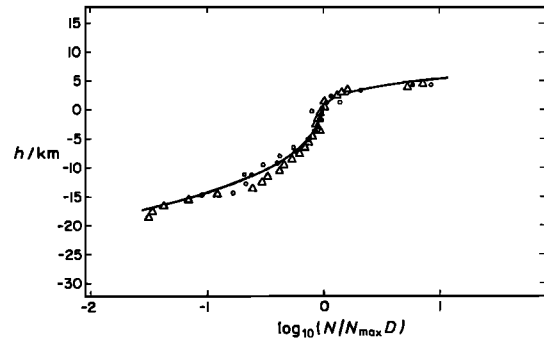


Fig. 4. Typical lower E region and D region electron density profile from different rocket in situ measurements [Mechty and Bilitza, 1974].

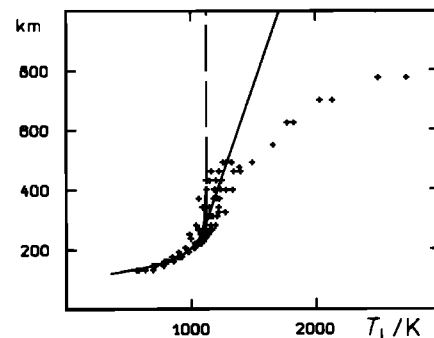
For the electron temperature the same sources of information are available. Unfortunately, many of the probe measurements are considered to be suspect, since they gave values of electron temperature that were often too high. Basic profiles were obtained from incoherent scatter measurements, the latitudinal variation being interpolated with satellite data, mainly from the Aeros satellites. In the E region the density is high enough to force the three temperatures to come together. In order to be in agreement with the neutral models of Cira it has been arranged that all profiles pass through the average Cira value of 335 K at 120 km. Typical temperature profiles based upon the Millstone Hill incoherent scatter facility measurements are shown in Figure 6.

Since the variations of heat conductivity are so important for the electron temperature, our program couples the electron temperature to a certain extent with the electron density, thus taking account of the inverse relation between both quantities, which is now well established [LeJeune, 1972; G. N. Taylor and R. J. Risk, 1974; Bilitza, 1975; Mahajan, 1977].

There are still problems with obtaining sufficient input data from some incoherent scatter stations. Our model is based mainly on the observations at Millstone Hill, Massachusetts, Arecibo, Puerto Rico, and Jicamarca, Peru.

ION COMPOSITION

Positive ions occur through the whole ionosphere, their counterpart being free electrons at all heights above about 84 km. Therefore electron and ion densities are equal, and a particular description of total ion density as such is not needed. The important parameter is ion composition, namely, the relative percentages of the main ions.



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Fig. 5. Daytime ion temperature profiles observed by the incoherent scatter technique at Arecibo, Puerto Rico.

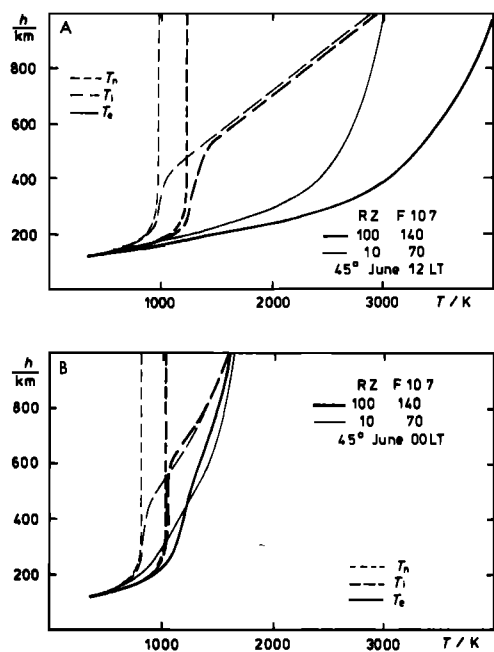


Fig. 6. IRI (1977) temperature profiles for electrons (continuous curves) and ions (dashed curves). Neutral temperature after Cirra for comparison (a) at local noon and (b) at midnight.

Our data sources depend on the height range considered. At satellite heights there are now a few reliable in situ measurements of the main ions, in particular from the retarding potential analyzer technique [Hanson *et al.*, 1970; Dumbs *et al.*, 1977] and from mass spectrometers [H. A. Taylor, 1971].

Unfortunately, not all these measurements are presented as relative densities. Absolute values of the density of an ion species are not very helpful for our purpose. In the height range below 100 km, useful results stem mostly from rocket probing, mainly with ion mass spectrometers. Two compilations of data were established by Danilov *et al.* [1977] from American, Russian, and a few European measurements. These data are the basis of our composition profiles. Not all conditions are met by these observations; in particular, true night observations are almost absent, and observations at low latitudes are sparse. Around the 100-km level, metallic ions are present and often form thin sporadic layers. These layers, occurring preferentially in the height ranges 92–95 and 110–115 km, are very variable and could not be included in the standard model.

The most difficult height range is below 100 km. Positive cluster ions are found below about 92 km and are the most abundant species below about 84 km. Investigations at such low altitudes are only available from three scientific groups, and it was not possible to establish a profile in agreement with all observations. A compromise profile has been proposed by A. D. Danilov (private communication, 1977). A recent result is shown in Figure 7 [Kopp *et al.*, 1977], and our typical ion composition profile in Figure 8.

Negative ions occur only at altitudes below about 80 km. However, they are of great importance in the D region. At lower altitudes they outnumber the electrons (which explains the steep gradient of electron density in the lower D region). Only the Heidelberg group [Arnold and Krankowsky, 1977] has experimental data about such negative ions, which are mainly clusters. In spite of some uncertainties we felt that

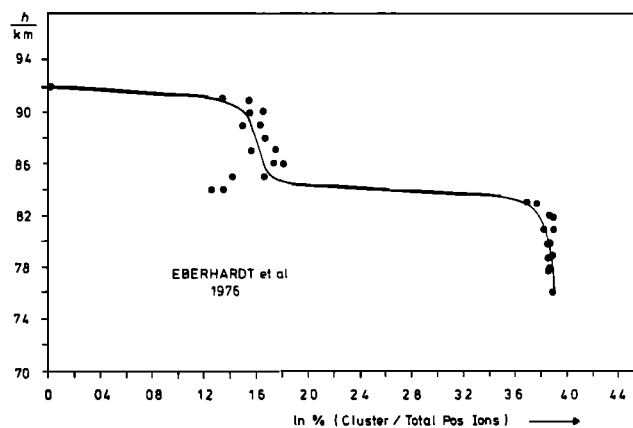


Fig. 7. An observed profile of positive cluster ions [Kopp *et al.*, 1977].

some provisional data should be reproduced in IRI. It is quite certain that more experience in this height range is urgently needed.

Figure 9 summarizes the sections on plasma density, temperature of electrons and ions, and ion composition; the experimental 'sources' are schematically linked with the relevant input parameters of our model.

#### REMAINING PROBLEMS

With the publication of IRI (1978) the project is entering its second phase. In the future the established profiles will be checked by comparison with new input data and with data from sources not previously used. This applies in particular to propagation experiments. Even if profiles cannot readily be established by inversion of such measurements, propagation experiments offer useful data for checking our profiles, for example, by computing absorption and comparing the results with those of experiments.

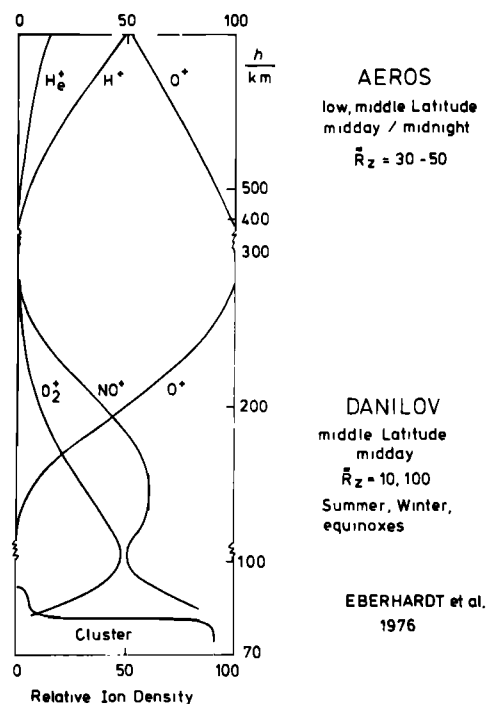


Fig. 8. Ion composition profiles through the ionosphere: data of the 1975 preliminary program (top and middle) and curve from Figure 7 (bottom).

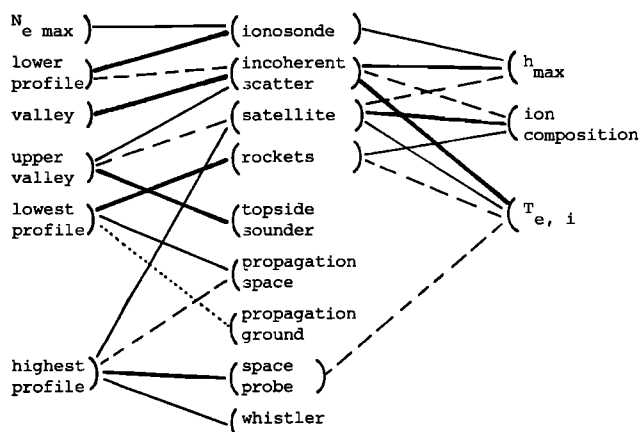


Fig. 9. Schematic diagram showing IRI parameters and problems and the relevant experimental data sources (center column).

A few comparisons of this kind were made with the 1975 preliminary profiles. H. G. Booker (private communication, 1976) made full-wave computations to explain Schumann resonances. He found that a slight change was needed in our profile shape of the lower  $E$  region and that the night valley above the  $E$  region should be less deep than that given in Soboleva's compilation (which was used for the 1975 preliminary tables). In the 1977 edition we have taken account of Booker's findings.

Quite recently, Singer *et al.* [1977] computed radio wave absorption in the MF and HF ranges and compared these data with ionospheric absorption measurements made in Europe with the pulse and continuous wave methods. He found that the 1975 model should be revised, in particular with respect to the solar cycle variation. At first sight, these results are not in agreement with the compiled rocket observations. Before a solution can be found, both sets of input data will be given in IRI (1978).

In the future, profiles will be given for altitudes above 2000 km but probably along magnetic field lines instead of the vertical. This task is dealt with by a special subgroup chaired by M. Rycroft.

The low-latitude temperature and composition models would benefit from considerably more observations than are available now. One important point is to incorporate satellite data. At lower altitudes, rocket and incoherent scatter measurements are particularly required.

Ion composition at the highest altitudes entails mainly the distinction between hydrogen and helium ions, the ratio of which might be quite variable. It is important to get satellite data in the form of relative composition instead of absolute ion densities.

More low-altitude ion measurements are needed with modern instrumentation such that cluster ions cannot be altered seriously at the entrance of the measuring instrument. Again, observations at low altitudes are completely absent at the present time.

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