

Can the IGY Global Ionosphere be Recovered?

Jan J. Sojka, Don Rice, and Vince Eccles

Space Environment Corporation
221 N. Gateway Drive
Providence, UT 84332-9791

ABSTRACT

The 1957-58 International Geophysical Year (IGY) is regarded by many as the threshold of mankind's entry into space exploration. Now 58 years later, we understand and can describe in detail the five complete solar cycles since then, and the differences between them. We know that the Earth's magnetic field has changed, causing changes in our planet's space weather shield. The Earth's atmosphere itself has also undergone changes, but has the interface region between space and our planet's atmosphere, the ionosphere and thermosphere, also undergone change? What could such changes tell us about changes in the atmosphere? Researchers have theoretically modeled the sensitivity of the ionosphere to hypothetical long-term changes in the atmosphere and have spent years of intense research to verify the results.

In this presentation, we address the question of whether it is possible to reconstruct the global ionosphere of the IGY era adequately to address these important questions regarding long-term change using our past and present knowledge of the ionosphere.

First, our present-day knowledge of the ionosphere prior to the space age will be assessed, particularly its limitations. Much of the knowledge we have regarding the mid-century ionosphere comes from hourly hand-scaled ionospheric sounding parameters pertaining to the E- and F-layers. Except for the IGY and specific research campaigns, most observations were tailored to operational HF radio wave propagation.

Second, we discuss the largely untapped archive of observations of the IGY-era ionosphere, which could provide a detailed representation of the historical ionosphere. Well over a hundred ionosondes were operating during the IGY and their records are preserved at various archive facilities. The archives include complete sequences of ionograms captured in various forms, particularly on 35 mm film reels. Available hand-scaled data are often hand-written and difficult to transcribe, and many of the records are limited to hourly observations, while the films generally record 15-minute or better cadence. Thus the bulk of these ionogram records await modern scientific processing to recover the full electron density profiles (EDP) contained in their o- and x-traces. In addition, the effects of planetary waves, tides, and other atmospheric disturbances can be analyzed with modern tools.

We will outline how ionospheric EDP can be obtained from archived observations. We will also review recent progress in ionogram conversion techniques, recovering data from the early 1950s. This will set the stage for an international effort to recreate an accurate IGY lower ionosphere.

1. INTRODUCTION

The research performed during the International Geophysical Year (IGY, 1957-1958) was the basis for much of the experimental and theoretical work in space physics for the decades that followed. Perhaps the greatest limitation in IGY studies was the lack of computational resources available at the time, forcing analyses to be restricted to special cases and subsets of the available data. Now that powerful computation capabilities are readily available, and sophisticated modeling tools have been developed, the IGY data set provides an excellent source for data mining and analysis.

For the decade prior to IGY through the present day, the ionosonde has been the instrument of choice to observe the lower ionosphere from the E and F₁ regions up to the main ionospheric peak of the F₂ layer. This region of interest lies above the altitude range of balloon-borne instruments and below typical low-Earth orbit (LEO) satellite access. Furthermore, the use of rockets to explore this region occurs infrequently, and the use of incoherent scatter radars (ISRs) to carry out these explorations, although scientifically more comprehensive, is extremely limited geographically, with less than 10 ISRs globally, and with a couple of exceptions is restricted to a few lengthy campaigns per year. Hence, our knowledge of the lower ionosphere from observations comes almost exclusively from the ionosonde. Indeed, these ionosondes have been operational longer and provide much larger global coverage than the other techniques.

Modern remote sensing methods are mostly passive, such as measuring optical 630 nm emissions from the ground or UV emissions from satellites; or L-band signals from navigation/positioning satellite constellations. These techniques produce line-of-sight integrated parameters which are related to the ionospheric electron density profile and the total electron content (TEC), but generally lack information about the structure of the height profiles. In both cases, extensive global coverage can be achieved, but these techniques have only been available at comprehensive levels for the past decade. Again, in contrast, the ionosonde networks have been in place for six decades.

The purpose of this paper is to provide a scientific rationale for expanding the knowledge of the global lower ionosphere to span from the 1950s to the present time. In particular, we present the case that the IGY itself is the definitive start date for global knowledge of the lower ionosphere and that this information has been archived, but only a small part of its potential scientific content has been analyzed. Thus this presentation makes the case for global funding for data mining to recover the IGY lower ionosphere. The ionosonde archives are still in reasonable condition and amenable to data mining [Rice et al., 2014]. These explorations will be described to establish what implications for global funding would be.

2. IGY IONOSONDE NETWORK

The international research community came together to formulate the IGY and found support around the globe among different nations to add scientific instrumentation to support the IGY observational objectives. One of these objectives was to comprehensively observe the ionosphere via high-frequency radio waves using ionosondes. Ionosondes would be located around the globe over a wide range of latitudes, literally from pole to pole. Figure 1 shows a geographic latitude/longitude distribution of the main IGY ionosonde network with continents faintly indicated to emphasize the geographic distribution. A total of 76 ionosondes are shown in this figure. These represent the subset of ionosondes that operated for at least 1.5 years from June 1957 and whose hand-scaled hourly ionogram analysis is included in the NOAA NGDC database CD ROM. The NGDC SPIDR on-line archive lists 100 ionosonde sites that were operational for varying periods during the IGY. Other

lists need to be prepared that describe the archival status of the ionograms, many of which were captured on 35 mm film and archived in the World Data Centers (WDC) The NOAA NGDC site was one of these WDCs.

This figure provides an indication of how effective the IGY was in covering all possible Earth locations. Looking at the extent of this distribution, it becomes an interesting exercise to evolve this distribution through the past six decades. In fact, such an analysis is rather negative since the distribution diminishes with time and only recently, during the past decade, has it shown signs of recovering. Therefore, the IGY ionosonde network offers unprecedented global coverage of the lower ionosphere. Based on the content of the original ionogram films, it is also true that less than 10% of the complete film observations are available today as scaled quantities in the archives. Without an international program of data conversion and preservation, the only way to access the large quantities of raw observations from IGY is to physically obtain and examine the reels of film.

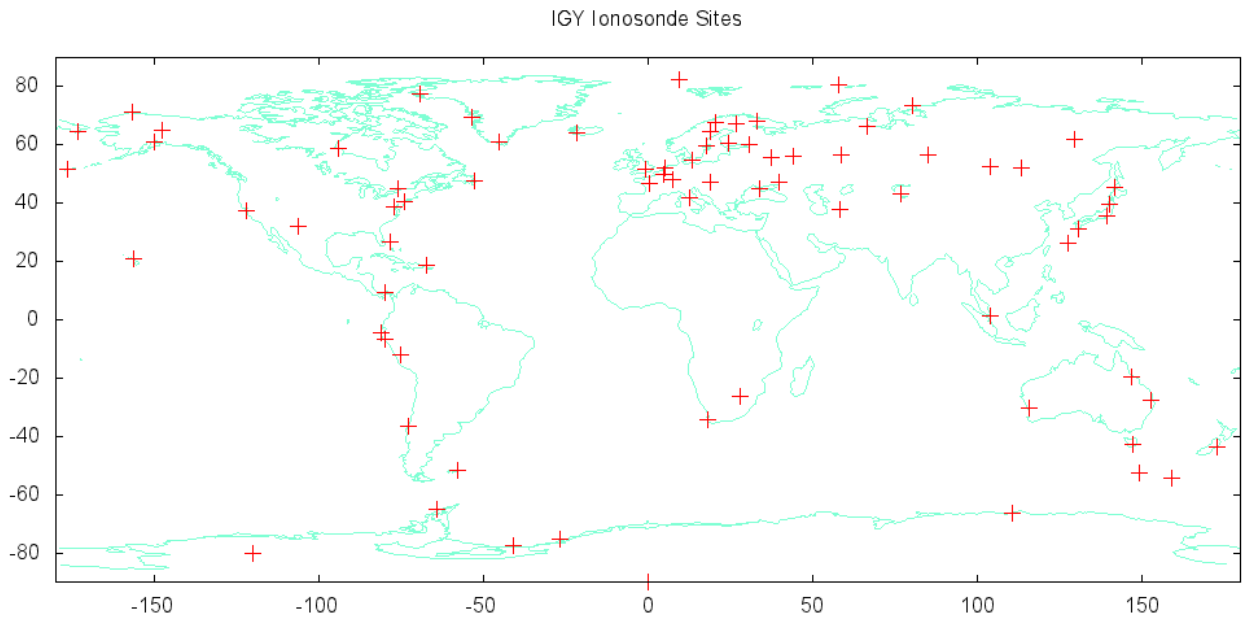


Figure 1. Distribution of IGY ionosondes.

3. SPACE WEATHER DURING THE IGY

The IGY could not have occurred at a better time to capture the global impact of space weather. Figure 2(a) shows the yearly average of the daily F10.7 Solar radio flux index from 1950 to 2015. Two vertical lines are drawn at 1957 and 1959, identifying the IGY period. This indicates that the IGY occurred during the most intense year of 10.7 cm radio emissions since 1950. As an aside, the International Polar Year 50 years later occurred at about the lowest year of 10.7 cm radio emissions (see 2007 in Figure 2(a)). The sunspot count over the same 65-year period shows the same trend and conclusion.

Geomagnetically, the Kp daily values averaged yearly provides a 65-year reference for weather in geospace (Figure 2(b)). In this instance, the IGY is not uniquely large but as the IGY vertical lines show, it is as active as several other periods of solar maximum. Therefore, both the solar and geomagnetic activity indicate that this period is ideal for space weather studies. Given the IGY ionosonde network, Figure 1, there is a unique opportunity to study space weather impacts not just locally, but more importantly on a global scale. Again in the post-IGY era, such studies were carried

out but these would be based mainly on hourly hand-scaled values where available. The negative ionospheric effects would, in general, simply be recorded as flags on the hourly values. Therefore, this aspect of data mining would be using almost pristine measurements.

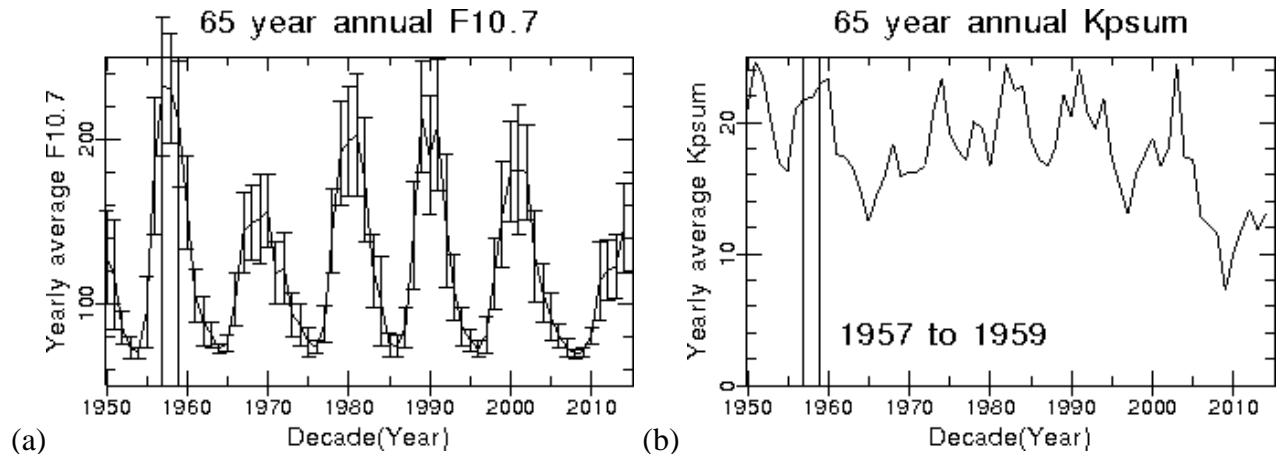


Figure 2. Geophysical indices for the last 65 years. (a) F10.7 solar flux index. (b) Annual Kp Sum.

4. SCIENTIFIC QUESTIONS

Many current scientific questions involving the lower ionosphere can be explored using the multidisciplinary IGY data sets, the ionosonde films in particular, in combination with modern computational and modeling capabilities.

Sporadic E. Sporadic E (Es) was of great interest in the IGY era due to its rather unpredictable nature and large impact on radio communications. Much effort was expended in mapping its occurrence [Smith, 1957], describing the various phenomena that fell under the “Es” label, and trying to correlate them with other observations and conditions [Whitehead, 1970; Whitehead, 1989]. These efforts led to the wind shear theory of midlatitude Es.

Modern Es studies with ISR and lidar have revealed temporal and height structures in great detail. Ionosonde Es records have been compared to lidar observations of sporadic neutral metal layers [Yuan et al., 2013; Friedman et al., 2013, and Yuan et al., 2014]. These studies consider the role of tides and gravity waves in the physics of how the mesosphere-lower thermosphere is coupled with the lower ionosphere through dynamics [Mathews, 1998]. The important questions are associated with time evolution and also spatial-regional extent. While IGY investigators conducted many investigations into Es behavior, the bulk of the scaled IGY ionogram data available today provides at best hourly flags of Es presence and in some cases, the critical frequency f_oE_s . However, the IGY film archive typically provides a 15-minute cadence, and the spatial distribution in certain geographic regions, i.e., Europe, would enable spatial scale studies to be undertaken. Exploring the distribution and life times of Es in the context of atmospheric waves, tides, and atmosphere-ionosphere coupling would provide information on scales that would be difficult to reproduce today. Indeed, today’s experiments usually lack large-scale spatial information which is essential for scientific analysis involving long-wavelength phenomena.

Descending layers. These features are closely associated with the Sporadic E phenomena but as shown by the detailed observations of the Arecibo ISR [Mathews, 1998], have independent complementary information. The layers were described as “sequential Es” by McNicol and Gipps [1951] due to their apparent motion across a sequence of ionograms, and were found to be a

common phenomenon in ionograms across a wide range of latitudes. The phenomenon may be associated with descending metallic layers [Yuan *et al.*, 2013]. Rice *et al.* [2014] showed an example of a descending layer in a sequence of film ionograms from Ft. Belvoir, 1951 day 335 (Figure 3.) Locating these features requires the 15-minute cadence ionograms found on the films; the archived hourly hand-scaled values do not have the temporal resolution to capture the descending layer.

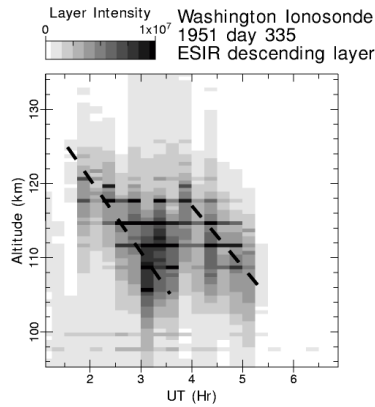


Figure 3. Descending layer from 1951.

Scientific questions regarding the formation of the layer and its downward motion are associated with tidal/gravity wave interactions between the ionosphere and atmosphere. The descending characteristics identify an atmospheric wave phase evolution with altitude as a function of local time. In turn, the IGY global ionosonde distribution would enable geographic analysis of these tidal characteristics. Again, the geographical distribution of present-day observational science facilities is generally inadequate for this type of study. The NSF has held workshops and supported studies to investigate how regional/global networks could be used to address such questions [NRC, 2006], but observational networks remain sparse. The IGY ionosonde distribution provides a suitable network that has been operational, whose data is archived, but awaits modern scientific analysis.

Bottomside ionospheric electron density profiles. The electron density profile (EDP) is viewed by most as the fundamental ionospheric information obtained from an ionosonde. Obtaining the EDP is a difficult inversion problem; the ionogram itself is a series of echoes produced as the transmitter frequency is swept across some range (typically, 1-20 MHz). The echo delay is retarded as the radio pulse propagates in the plasma of the ionosphere. Various methods exist to invert the echo “virtual height” profile into the “true height” EDP, requiring various levels of computational capability [Titheridge, 1985]. These resources were not available to the hand scalars of the IGY and post-IGY analysts. Instead, EDPs were approximated with graphical methods involving assumptions about the shapes of the lower layers. Hence, the few EDPs produced for IGY studies could be regarded as first-order approximations by modern standards.

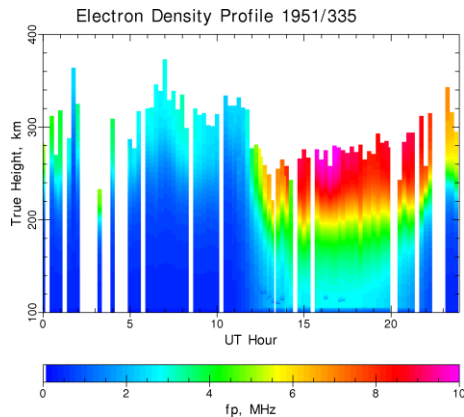


Figure 4. EDPs obtained by modern analysis of 1951 film ionograms.

However, the confusion and differences in results all point to the need for a more accurate and consistent global lower ionosphere altitude description.

Modern autoscaling methods can be applied to the film ionograms, and have the advantage of providing a consistent methodology, more sophisticated mathematical inversions, and the ability to specify uncertainties on the profile. *Rice et al.* [2014] described the application of such procedures on film ionograms from 1951 (Figure 4.) There are limitations to these methods. For example, the calibration of the ionosonde frequency and height ranges depended on the diligence of the operators. There is also general uncertainty about the existence and depth of the valley region between the E and F₁ region which affects the determination of true heights (altitudes) of the electron density profile above this valley region [*Titheridge*, 2003].

Ionospheric response to space weather. One of the unique accomplishments of the IGY was the first use of rocket and satellite measurements, including two US rocket flights to 63,000 and 73,000 miles altitude that discovered unsuspected radiation belts [*Chapman*, 1959]. However, the effects of solar wind, interplanetary magnetic field orientation, and other fundamental space weather quantities remained to be appreciated. Space weather measurements primarily consisted of sunspot number, radio flux (F10.7), magnetic indices, and ionospheric critical frequencies from ionosondes. In preparation for the IGY, Fort Belvoir, near Washington D.C., was given the primary responsibility for issuing alerts and warnings for IGY campaigns and for designating Special World Intervals (SWIs) when major solar terrestrial disturbances were expected [*Moore*, 1957]. Fort Belvoir collected available space weather data and operated an ionosonde from 1948-1968. The IGY solar maximum proved to be particularly active, providing many opportunities for coordinated SWI global observations. *Chapman* [1959] noted that the alerts predicting active periods were made “with fair success,” given the limited information available.

The combination of routine observations, pre-planned World Days with increased observations, and SWIs meant that the lower ionosphere was uniquely well monitored by the IGY ionosonde network. This network monitored the global lower ionosphere at levels of coverage not possible today. Usually, when strong solar flares or geomagnetic activity is present, the ionograms are hard to analyze due to absorption or spread F, and the hand-scaled record indicates that analysis was impaired by space weather. However, the full global measure of how impacted the ionosphere was exists at 15-minute cadence in the IGY archive, and the aftermath of storms, such as large-scale traveling ionospheric disturbances (TIDs) were crucial to the understanding of waves in the upper atmosphere [*Hines*, 1959]. Again this level of global coverage of the impact of space weather on the lower ionosphere has not been achieved since. Because many severe storms occurred during the IGY, many strong impacts on the ionosphere were recorded in detail, and could be analyzed with modern tools to obtain new insights on severe storm impacts and the propagation of large-scale atmospheric waves.

Climate versus weather. Since the IGY period was extremely rich in space weather activity, the question arises of whether the quiet periods were of sufficiently long duration to provide information on the IGY ionospheric climate. Establishing the climatological behavior is particularly important for studies of long-term change. Hence, a complement to the study of severe space weather is the search for the climate in the IGY archive. Note the hand-scaled data will potentially have relevance to this study since under quiet space weather conditions, the ionograms will be good and hand-scaled values will be accurate. In addition, the solar minimum prior to IGY (1954) was remarkably quiet, so climatological studies could be extended back to that period for the much smaller set of ionosondes that was operating and archived data prior to IGY.

5. CONCLUSIONS

The International Geophysical Year produced a unique and comprehensive multi-instrument data set with global coverage. It was used to develop theoretical frameworks that are the basis for space physics theories and models still in use today.

Many of the archived IGY data sets are still available today, and the film ionogram archive in particular could serve as a rich set of observations for comparison to modern theories and models. These observations, and similar observations extending back at least a decade prior to IGY, may also hold clues to any long-term changes in the ionosphere and upper atmosphere that have occurred in the last six or seven decades. Unfortunately, the film records are extremely difficult to work with in their original form, so conversion to digital format is crucial to the preservation and use of this valuable data set.

The procedure for converting and analyzing the historical ionograms has been described by *Rice et al.* [2014]. Once in digital form, the data sets can be used by researchers worldwide. Comparisons with modern models can be made, though some work may be needed to extend models into the past. *Rice and Sojka* [2015] describe the modification of IRI for use in the pre-IGY period.

The availability of this comprehensive, global historical data set highlights the lack of a comparable modern data set, and argues for the implementation of the Distributed Array of Small Instruments (DASI) concept described in the NRC [2006] report. Addressing global concerns requires a reliable and consistent global data set.

C. O. Hines [1959] summed up the challenge following IGY: “A wide variety of motions has now been revealed, and virtually all of these require examinations on a world-wide basis to insure proper interpretation. The extensive supply of IGY data, if analyzed as assiduously as it has been accumulated, may be expected to resolve many of the problems which have so far been encountered.” The challenge remains today to use this global data set to test and extend modern theories and models across the decades.

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