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Validation of In Situ Ionospheric Density Measurements with Ground-Based Radar

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The in situ sensors aboard spacecraft of the Defense Meteorological Satellite Program routinely measure top-side ionospheric ion densities near 840 km. This report presents data that demonstrate that the satellite ion density measurements are accurate. This verification is done by comparing the ion densities determined by the thermal plasma instrument with plasma densities determined by the incoherent scatter radar station at Millstone Hill, Westford, Massachusetts. The radar measurements were obtained at nearly the same location and same time as the satellite measurements and are completely independent of the satellite observations. This report describes the collection and comparison of the radar and spacecraft data for the years 1989 and 1991. The principal result of the study is that ion densities determined by the spacecraft differ from radar plasma densities by less than 10%.

Nomenclature

Kp = three-hour planetary geomagnetic activity index
N_e = number density of electrons, cm^{-3}
N_i = number density of ions, cm^{-3}
R = linear correlation coefficient
σ = standard deviation

Introduction

THE satellites of the Defense Meteorological Satellite Program (DMSP) are a series of polar-orbiting spacecraft with orbital heights of 835–850 km. There are nominally two satellites in operation at all times. The spacecrafts are in orbits that are fixed in local time with equatorial crossing times near 06:00 (ascending node) to 18:00 (descending node) and near 09:00 (ascending node) to 21:00 (descending node). Their primary mission is to observe the tropospheric weather. The principal sensor system used to accomplish this mission is the Operational Linescan System, a high-resolution (2.8-km), white-light, and infrared imaging system.

The secondary mission of DMSP is to monitor the near-Earth space environment, which is important to the U.S. Air Force because of the various ground-based and space-based systems that can be affected by changing conditions in space. The principal system for this task is the Topside Ionospheric Plasma Monitor plasma package, which measures parameters of the in situ thermal plasma (density, ion composition, ion temperature, and electron temperature) along the satellite flight path. The plasma instruments have been previously described.[1,2]

The DMSP plasma package has been tailored to the space environment at 840-km altitude at all latitudes, local times, seasons, and solar cycle variations. Typically, this environment consists of the three major ion species for oxygen (O^+), hydrogen (H^+), and helium (He^+). Plasma densities for both ions and electrons typically vary from 10^3 to 10^6 cm^{-3}. At midlatitudes the day to night electron temperatures range from approximately 3500 to 1200°K, respectively. These temperatures increase and decrease with solar activity. The corresponding ion temperatures at this altitude are typically comparable to but less than the electron temperatures owing to collisional effects between the gases and ion cooling from thermal conduction.

DMSP plasma data have been taken and archived in an electronic form since mid-1987. The data are used operationally by the U.S. Air Force as input to space environmental computer codes. Because the accuracy of the satellite measurement technique affects the output of this software, as well as the geophysical interpretation of the data, it is important that the DMSP density measurements are validated, that is, compared to a credible standard for accuracy.

Although the U.S. Air Force Research Laboratory has informally compared DMSP density measurements to ground-based incoherent scatter radar data and periodically compares ion and electron density measurements between instruments on different DMSP spacecraft, a rigorous, documented validation of the density data has never been performed. An important reason for this is the inherent difficulty of obtaining reliable independent density measurements at top-side altitudes.

Incoherent scatter (IS) radar is one of the few measurement techniques that can provide a reliable observation of the top-side ionospheric density. Overflights of the spacecraft over ground-based IS radar sites thus offer the opportunity to validate the satellite measurements with coincident IS density observations.

An early study of this type was conducted in a limited way in the early 1960s in which top-side sounder data were compared with incoherent scatter and in situ sounding rocket density measurements.[3,4] Although only a case study of a single event, this work identified IS radar measurements as being in excellent agreement with in situ probe and sounder data.

A similar study was performed using Atmospheric Explorer-C overflights of an IS radar site.[5] Two cases from February 1974 show daytime IS and in situ electron densities near 160-km altitude agreeing within 33%.

Because IS data have been taken and archived since at least the 1970s and given the similarly long time series of DMSP data, it is likely that there are enough simultaneous measurements of a common volume of space by both instruments to provide a statistically valid verification of the spacecraft data accuracy. This report describes the collection and comparison of archival incoherent backscatter radar and DMSP data for nearly concurrent DMSP overflights over several years.

DMSP Ion Density Data

The DMSP data considered here are from the scintillation meter (SM) and retarding potential analyzer (RPA) instruments, which measure total ion density (N_i) and composition along the satellite flight path. When the ambient ion density exceeds the upper range of the SM instrument of 1×10^6 cm^{-3}, which occurs frequently near the magnetic equator during the active phase of the solar cycle, a diagnostic output of the ion drift meter, which has a higher saturation level, provides the ion density measurement.[6] Figure 1 shows typical DMSP ion density and electron temperature data from the F10 spacecraft RPA for a late evening pass during 1991. Ion density and electron temperature data are plotted from −60 to +60 deg

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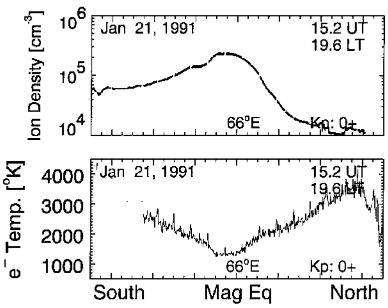

Fig. 1 Typical DMSP F10 plasma data from 1991.

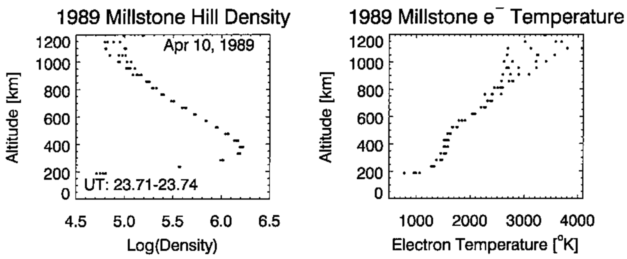

Fig. 2 Sample altitude profiles of Millstone Hill Incoherent Scatter Radar electron density and electron temperature during 1989.

magnetic latitude. Panel labels give the date, local time, universal time, Kp index, and geographic longitude of the spacecraft as it passes over the magnetic equator.

Millstone Hill Incoherent Scatter Radar Data

Incoherent scatter radar density data for this study were selected from the on-line database of the Millstone Hill UHF radar in Westford, Massachusetts. The Millstone data set was chosen for its reliability as well as for reasons of ease of accessibility of data. Other possible radars for additional validation studies include the Arecibo, Puerto Rico; the Sondrestrom, Greenland; the Jicamarca, Peru; and the EISCAT Scandinavian IS facilities.

The Millstone Hill radar is operated by the Massachusetts Institute of Technology Haystack Observatory Atmospheric Sciences Group. The geodetic latitude and longitude of the radar are 42.62°N, 288.51°E. The invariant latitude is 53.41°N. The radar system consists of two 2.5-MW 440-MHz transmitters, a fully steerable 46-m antenna and a zenith-directed, 68-m fixed antenna.

The incoherent scatter technique uses Thomson backscatter from ionospheric electrons to deduce height- and time-resolved plasma drift velocities, electron and ion temperatures, electron densities, ion composition, and ion-neutral collision frequencies.[7] The Millstone IS data set provides observations of these parameters over an altitude range extending from less than 100 to 1000 km or more. Figure 2 shows typical Millstone Hill electron density (N_e) and electron temperature altitude profiles from 1989. The date and universal time of the profiles are given in the left-hand panel.

Methodology

The study was undertaken in the following way: first, Millstone Hill incoherent scatter radar electron density data for several years were downloaded from the database on the Millstone Hill website (www.haystack.edu/homepage.html). The data were sorted to include only vertical profile data (elevation angle $\geq 88°$), extending in altitude from the bottomside (200 km) to the topside (850 km). The years 1989, 1991, 1992, and 1998 were selected to sample the different parts of the solar activity cycle. The local times and day of year of the Millstone data for 1989 and 1991 are shown as the vertical lines in Fig. 3.

Next, the DMSP data set was searched for cases where the spacecraft flew within a 5° wide latitude/longitude circle of the Millstone radar. All ion density data points along the flight path that were within this circle were averaged to obtain a data point for comparison with the radar density measurement. These cases are indicated in Fig. 3 by the horizontal lines. The number of each spacecraft is indicated to the right of each panel. The intersection points of the horizontal and vertical lines represent candidate cases for DMSP data validation. In 1989, data from the F8 and F9 spacecraft were available, yielding four local times for potential data comparison. In 1991, F8, F9, and F10 data were available, yielding six potential comparison times.

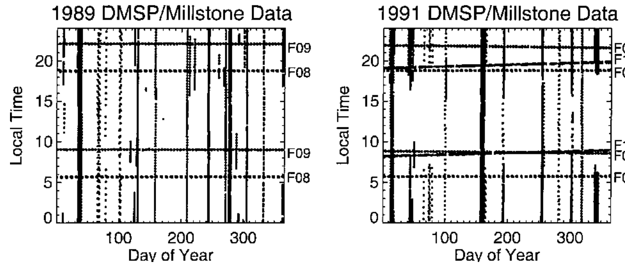

Fig. 3 Local time and day of year for Millstone Hill (vertical lines) and DMSP (horizontal lines) top-side density data.

The Millstone and DMSP data sets were next searched for cases in which the radar and the spacecraft made density measurements close by in time. The time limit for this study was selected to be 30 min. Finally, the radar data were required to have at least two sequential altitude profiles. The radar data were averaged over ±25 km of the satellite altitude and over ±30 min of the DMSP overflight time to obtain a data point for comparison with the satellite density data. Cases in which either the radar or spacecraft data were not reliable were neglected. In some cases the scatter in the radar data was too great, and in others the latitudinal gradient in satellite density was too great, as often occurred during geomagnetic disturbances.

This selection process generated 31 cases of near-simultaneous radar and satellite density measurements during 1989 and 1991. Because of the lower electron density levels at 840 km during solar minimum (from mid-1992 to 1998) and because of different operational modes of the Millstone Hill radar during this time, there were only a limited number of cases in which there were simultaneous radar and in situ DMSP data. The few cases that existed were found to have radar data with low signal-to-noise ratio, and so this study was limited to the solar maximum years 1989 and 1991.

Results

Figure 4 shows sample results for one case from 1989. The top panel gives an overview geographic map showing the DMSP ground track and the location of the Millstone radar.

The middle panel shows the DMSP ion density observed during the overflight. The thick line segment near 55°N magnetic latitude indicates when the satellite was near overhead of the radar ground site. The bottom panel shows the Millstone radar density profile taken during the DMSP overflight. Note the increase in the radar noise level above 900 km as the returned radar signal level from the ambient density drops off.

A direct comparison between between the averaged radar and in situ measurements is shown in the bottom panel, which plots the radar density altitude profile (small points) during the overflight. The star is the averaged satellite density measurement, and the open circle is the average of the radar density measurements. This comparison yields excellent agreement (within 2%) between the two data sets. There are, of course, inherent uncertainties in both the radar and satellite data as a result of the averaging of measurements over distance, altitude, and time. As will be discussed, these measurement uncertainties generally fall within the percent differences between the two data sets. Table 1 lists the parameters of all 31 cases that were identified over the two-year study.

Figure 5 shows a summary scatter plot of all of the available cases. The dotted line indicates where perfect agreement would be between the two data sets. When a line is fitted through the data points, a linear correlation coefficient $R = 0.98$ is derived. The difference between the resulting fitted line (solid line) and the dotted line indicating perfect agreement is not statistically significant. Figure 6 shows the error analysis of this data. The top panel plots the percent difference between the radar and DMSP data for all 31 cases. The average difference is found to be under 2%, with a standard deviation of ±11%. There is no identifiable bias in the spacecraft data, which

Table 1 Listing of DMSP and Millstone radar cases

DMSP	Date	Kp	DMSP UT	DMSP N_i	Radar UT	Radar N_e	Percent difference
F08	4 Oct. 1989	1−	10.72	4.634	10.58	4.587	11.4
F08	5 Oct. 1989	1o	10.51	4.558	10.48	4.643	−17.7
F08	6 Oct. 1989	3−	10.27	4.655	10.33	4.614	9.8
F08	19 March 1989	3−	23.35	5.190	23.44	5.144	11.2
F08	11 April 1989	2o	23.76	5.249	23.72	5.234	3.4
F08	11 April 1989	2o	23.54	5.220	23.72	5.190	7.1
F08	12 April 1989	2o	23.35	5.116	23.30	5.074	10.0
F08	2 Oct. 1989	1o	23.47	4.996	23.38	4.995	0.1
F08	3 Oct. 1989	2+	23.28	5.201	23.29	5.126	18.9
F09	12 April 1989	2−	14.06	4.914	13.95	4.896	4.2
F09	4 Oct. 1989	2o	14.04	4.929	14.02	4.944	−3.4
F09	5 Oct. 1989	2o	13.68	4.930	13.64	4.925	1.2
F09	28 Nov. 1989	4o	13.82	4.966	13.81	5.006	−8.8
F09	11 Jan. 1989	2o	2.64	4.595	2.66	4.591	0.8
F09	11 April 1989	3o	3.00	4.958	2.86	5.058	−20.5
F09	12 April 1989	2o	2.68	5.090	2.79	5.109	−4.2
F09	4 Oct. 1989	2o	2.64	4.997	2.62	4.968	6.9
F09	28 Oct. 1989	2o	2.90	4.396	2.84	4.381	3.4
F08	12 July 1991	6−	10.41	4.680	10.40	4.600	20.3
F08	13 Feb. 1991	3−	23.76	4.851	11.72	4.798	13.0
F08	13 Feb. 1991	3−	23.54	4.926	23.52	4.873	13.0
F09	15 Jan. 1991	2+	13.41	4.517	13.44	4.471	11.1
F09	13 Feb. 1991	3−	13.32	4.678	12.94	4.682	−1.0
F09	13 Jan. 1991	4o	2.73	4.420	2.74	4.499	−16.6
F09	18 Jan. 1991	3−	2.66	4.331	2.60	4.426	−19.5
F09	12 July 1991	3o	2.76	4.867	2.77	4.851	3.8
F09	9 Dec. 1991	1o	2.61	4.439	2.55	4.412	6.4
F10	13 Feb. 1991	3−	12.74	4.760	12.68	4.743	3.9
F10	14 Nov. 1991	4o	0.81	4.953	0.75	4.971	−4.0
F10	7 Dec. 1991	1+	0.74	4.523	0.75	4.530	−1.7
F10	11 Dec. 1991	4−	0.36	5.027	0.38	5.067	−8.9

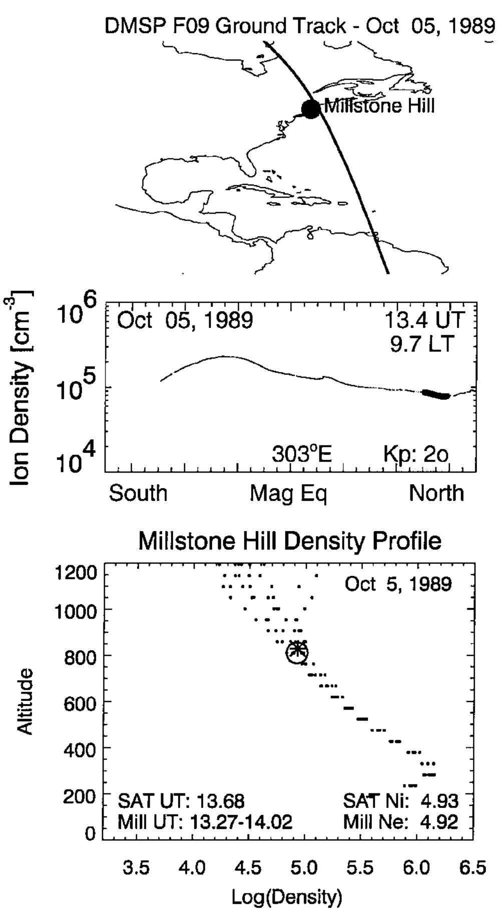

Fig. 4 Near simultaneous Millstone Hill and DMSP density measurements during 1989.

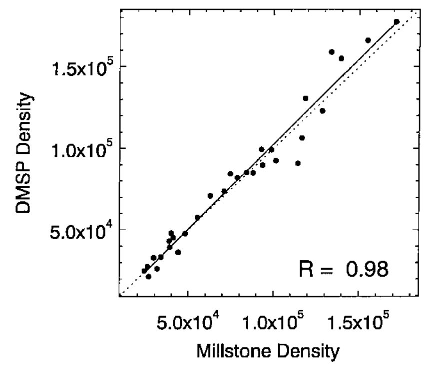

Fig. 5 Scatter plot of the 31 available Millstone Hill and DMSP topside density cases.

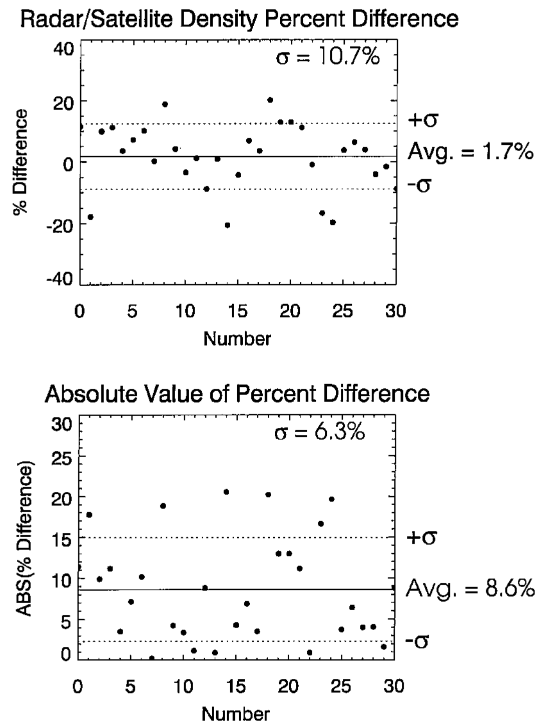

Fig. 6 Percent differences between the Millstone Hill and DMSP topside densities.

would have indicated that the spacecraft either was systematically over- or underestimating the ion density. Additionally, there are no obvious trends in the percent difference data when the cases are sorted by distance in time or space from the radar, indicating that the ionosphere was fairly uniform both temporally and spatially within the parameters of the data comparison (±30 min and ±5 deg); thus, these comparison parameters are reasonable to use.

However, a computer code that uses DMSP density inputs will not distinguish between an input that is a few percent too high or a few percent too low: the resulting program output will be biased in either case. A more meaningful number for validation purposes is the absolute value of the percent differences, which tells the user how far a given satellite density measurement is from the actual density, thus giving a crude measure of how much the resulting software output might potentially be biased. This number is plotted in the bottom panel of Fig. 6. In this case there is an average absolute percent difference of 8.6% between the two data sets, with a standard deviation of ±6%.

As was noted, there are uncertainties caused by the averaging of measurements in both the radar and satellite measurements. The statistical uncertainty of the radar data points (taken as $\sigma/\sqrt{N}$, where N is the number of radar data points in the average) is 6.4% ±3.8%. Additionally, there is an inherent uncertainty in the DMSP density measurements as a result of the sensitivity of the instrument. The

RPA has a range of 10^1–10^6 cm^{-3} with a sensitivity of 0.01, which means that a one-bit change in the RPA data represents a 2.3% change in ion density ($10^{0.01} = 1.023$). The RPA thus is unable to detect density changes below 2.3%. Both the radar uncertainty of 6.4% and the DMSP uncertainty of 2.3% are within the overall average absolute percent difference of 8.6% between the two data sets.

Conclusions

A total of 31 cases where the Millstone Hill IS radar was operating when a DMSP spacecraft was flying overhead have been identified in the 1989 and 1991 DMSP/Millstone data sets. There is found to be excellent agreement (correlation coefficient $R = 0.98$) between the radar and satellite density data sets. Based on these results, an overall error of around 9% can be quoted for the reliability of DMSP total ion density data. This number conforms with the commonly quoted 10% error for DMSP density data. Extending this study to additional years or ground sites will yield a larger number of cases for comparison, but it is not expected that the results will be significantly changed. The next logical step in this work is to pursue the radar-measured electron temperatures and compare them to in situ electron temperature measurements for validation of the DMSP electron temperature instrument.

Acknowledgments

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