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Comparison of T_e and T_i from Ogo 6 and from Various Incoherent Scatter Radars

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Langmuir probe and retarding potential analyzer (RPA) data on the electron and ion temperatures T_e and T_i obtained from Ogo 6 are compared with T_e and T_i values obtained from the incoherent scatter network. The satellite to radar temperature ratio T_{eS}/T_{eR} is 1.15 on the average for these comparisons. This discrepancy is larger than the uncertainties usually placed on the probe and radar T_e values. It is, however, a smaller discrepancy than that found in many previous comparisons of this type. Our data do not appear to give any insight into the cause of the discrepancy. The ion temperature ratio T_{iS}/T_{iR} is approximately 1.0, independent of the particular radar examined. The internal accuracy of the RPA T_i data set was ±5% or better. Thus this comparison serves as an intercalibration of the incoherent scatter network. Since no significant systematic errors (i.e., errors larger than the statistical errors) exist between the RPA and radar T_i data, it appears very unlikely that any significant systematic errors exist in either data set. It should be noted, however, that the comparison data were limited to mainly nighttime hours and thus to relatively low temperatures and were heavily weighted to altitudes between 400 and 600 km, where suspected sources of systematic error are minimum.

Conflicting measurements of electron temperature T_e obtained at the Jicamarca Radar Observatory and from satellite Langmuir probes were first reported by *Hanson et al.* [1969]. Similar discrepancies were soon reported from other incoherent scatter observatories. The nominal satellite to radar temperature ratios T_{eS}/T_{eR} of 1.7 for Jicamarca, Peru, 1.4 for Millstone, Massachusetts, and 1.4 for Arecibo, Puerto Rico, were discussed at a special session of the 1969 Annual Meeting of the American Geophysical Union, which was partly documented by *Carlson and Sayers* [1970]. This conflict has not yet been resolved, although much effort has been expended.

Some rocket-based T_e profiles [*Brace et al.*, 1969] agreed approximately with radar T_e profiles up to approximately 350 km. One rather indirect comparison with the rocket ~5000 km from the radar but at nearly the same (small) dip latitude resulted in fairly good agreement up to ~350 km altitude, but the agreement became increasingly poor above this altitude, the probe to radar T_e ratio being 1.8 at 700 km [*Brace and McClure*, 1971]. This result has suggested that the problem is somehow altitude dependent and hence that it might be resolved by a geophysical explanation. However, among the comparisons of *Hanson et al.* [1969] the largest conflict, a T_e ratio of >1.8, occurs for the lowest altitude, 366 km.

Another radar-satellite comparison [*Taylor and Wrenn*, 1970] showed no T_e conflict: ($T_{eS} - T_{eR}$) was within ±10% of the mean value in all cases, and, although the overall uncertainty of some of the T_e values was relatively large (~±40%), it was <±10% in other cases. Taylor and Wrenn used a Langmuir plate hav-

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ing a faster sweep rate [cf. *Carlson and Sayers*, 1970] than the cylindrical probes used in the present and in all the previously mentioned comparisons. The cylindrical probe–radar conflict in T_e still continues. For the new T_e comparisons we present here the average value of $T_{eS}/T_{eR} = 1.15$, which is much less than the value given in some of the previous comparisons but still significantly greater than 1.0.

A conflict has also been discovered between Jicamarca values of ion temperature T_i and values obtained from the retarding potential analyzer (RPA) on Ogo 4 [*McClure and Troy*, 1971]. The ratio T_{iS}/T_{iR} was 1.2–1.4 for these comparisons. An examination of the systematic error in these RPA measurements caused by electric field penetration of the sweep grid has been made by *Hanson et al.* [1972], who find that this effect should cause the Ogo 4 T_i results to be 15% too high. More recently, *Yadlowsky et al.* [1972] have suggested that, when focusing effects due to the transverse electric fields near the grid plane are also taken into account, the Ogo 4 systematic error in T_i is increased to +25%.

A large body of RPA data having a relative T_i precision of better than 5% was obtained from Ogo 6 [*Hanson et al.*, 1970]. We present a comparison of this data set with data from the incoherent scatter network. The T_i values always agree to within the sum of the respective uncertainties of each given comparison. Furthermore, in almost all cases the values agree to within a few percent; this agreement implies that at least for these cases it is highly unlikely that there are large systematic errors in either the satellite or the radar techniques and that the observed random errors, which are near the expected theoretical limits for both the radar and the satellite data, are often the only errors that need be considered.

We will not discuss the experimental techniques in use at the various radar observatories, since they have been reviewed by *Evans* [1969], *Hey et al.* [1968], and others (cf. Evans). In the following sections we briefly describe the satellite experimental techniques and results, then consider some of the details of the comparisons, and finally summarize our findings.

Langmuir probe. The cylindrical Langmuir probe has been used to measure ionospheric electron temperatures and densities for nearly a decade [e.g., *Spencer et al.*, 1962; *Taylor et al.*, 1963; *Nagy et al.*, 1963; *Brace et al.*, 1971]. Two such probes were used on Ogo 6; they were mounted at right angles to each other on the orbital plane experimental platform (Opep), as is shown in Figure 1. As long as the spacecraft was in its normal operating mode, probe 1 always pointed at right angles to the velocity vector, and probe 2 was usually parallel to it; however, the Opep could be rotated in such a manner that the angle between probe 2 and the velocity vector varied from −180° to +180°, while probe 1 stayed at right angles to the velocity vector. Such scans allow the angle-of-attack dependence of the probes to be studied. The results of such a study will be the subject of a separate paper; for the comparisons presented here the angle-of-attack effect is negligible.

The probes, made of stainless steel, are 23 cm long and 0.56 cm in diameter. Concentric 23-cm guards keep the probes away from the mounting fixture in order to minimize electric field and sheath distortions. It was possible to use

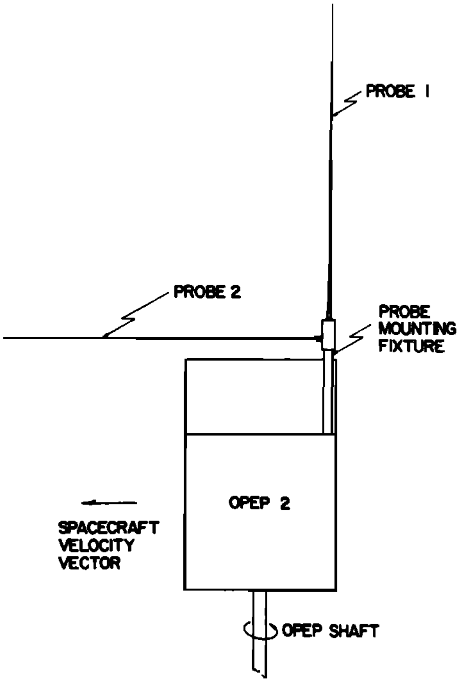

Fig. 1. The two cylindrical Langmuir probes shown in their location on Ogo 6. The RPA (not shown) is located on the forward-looking face of the Opep.

the probes alternately or to use only a given probe; probes were alternated at least every 36 sec during the operating lifetime of the satellite.

The electronics were housed in the main body of the satellite and consisted basically of (1) the sweep voltage system, (2) the current detector units, and (3) the associated logic circuit. Two current detector systems were employed: system 1, which consisted of a sequentially switched two-range logarithmic current detector covering a dynamic range of about 4 decades, and system 2, which consisted of a sequentially switched four-range linear unit also covering a range of about 4 decades. In general, the linear and logarithmic systems were alternated every few days, although toward the end of operations the logarithmic detector was used more frequently. Both the collector and the guard were driven by a 9-sec 6-volt linear sweep. The sweep voltage associated with system 1 had a 'search unit,' which found the floating potential (the applied voltage for zero net collected current) and set the sweep to start 2.5 volts below this value. System 2 did not have such a search unit, but the sweep voltage bias could be selected by command from the following six values: 0, 2, 4, 6, 8, and 10 volts. The data quality was, in general, very good for both the linear and the logarithmic systems; Figure 2 shows typical data segments from both systems.

The electron temperature comparisons made in this study are listed in Table 1. A total of 19 points appear along with the date, time, radar installation, and altitude for which the comparison is made. Originally, it was hoped that a much larger number of comparison points would be available so that the data could be subdivided according to important theoretical plasma parameters: the ratio of the probe dimension to the Debye length, the local temperature gradient, the altitude, and so forth. Unfortunately, only a limited number of comparisons were available. For example, owing to the failure of a string of solar cells shortly after launch, a highly negative spacecraft potential (13–20 volts) appeared whenever the satellite was sunlit, and, as a result, practically no daytime probe data were obtained. Other problems included incomplete altitude coverage by the radars, intermittent operations, and so forth.

The main result seen from Table 1 is that the electron temperature obtained from the probe usually exceeds that from the radars. The magnitude of the discrepancy can be gaged by simply averaging the ratios T_{eS}/T_{eR} for the 19 points of Table 1. The result is 1.15, less than the 1.4–1.7 values from earlier satellite comparisons [*Carlson and Sayers*, 1970] but still greater than can be explained by routine error analysis applied separately to probe and radar data. In Figure 3 the temperatures of Table 1 are graphed to display the results in a simpler form. Each point in Figure 3 carries some uncertainty due to experimental errors, the distance between the satellite and the radar beam, interpolation (in altitude or time) of data, and the fact that probe current-voltage curves were taken at several points as the satellite flew overhead. Rather than attempt to lump these ionospheric and instrumental uncertainties into error bars for the points of Figure 3, we presented the detailed information in Table 1: the number of current-voltage curves taken within the listed latitude and longitude of the radar, the observed temperature ranges of the probe and the radar, and, when they are available, the statistical uncertainty in the radar temperature.

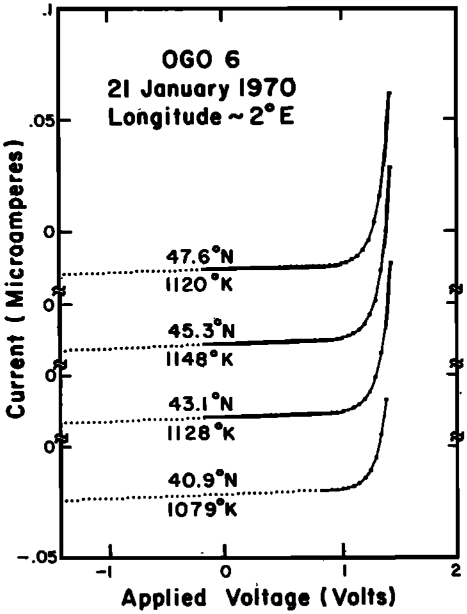

Fig. 2. An example of typical Langmuir probe data corresponding to the radar satellite comparison illustrated in Figure 5. The geographical latitude is shown for each curve; the CNET radar is located at approximately 45°N, 3°E.

TABLE 1. Electron Temperature Comparisons

Station	Date	UT	Δt, min	Altitude, km	T_e Probe, °K	T_e Probe Range, °K	T_e Radar, °K	T_e Radar Range, °K	Latitude Offset	Longitude Offset	Number of Probe Points
CNET	Oct. 22, 1969	0112	±1	506	1258	1208–1309	965 ± 25		+2 to −4	+6	2
	Nov. 13, 1969	2157	±97	432	1266	1059–1448	930 ± 30	930–1100	+13 to −20	+33 to −18	16
	Jan. 19, 1970	2358	±1	478	1215	1138–1274	950 ± 35		+6 to −3	+15	4
	Jan. 20, 1970	0140	±1	460	1036	994–1084	950 ± 35		+3 to −6	−8	3
	Jan. 21, 1970	0049	±1	460	1115	1079–1148	960 ± 20		+3 to −3	0	4
	Feb. 17, 1970	2159	±1	505	1202	1143–1234	1110 ± 30	1100–1150	+4 to 0	−10	4
	Feb. 18, 1970	0912	±1	460	2927	2749–3147	2550 ± 40	2500–2600	+2 to 0	+16	3
	Feb. 18, 1970	2110	±1	525	1380	1301–1478	1200 ± 40	1150–1300	+2 to −2	−1	3
Arecibo	Aug. 7, 1969	0308	±1	1070	1369	1251–1488	1300 ± 150		+1 to −3	+3	2
	Oct. 10, 1969	0703	±1	836	1316	1271–1362	1100 ± 110				2
	Nov. 13, 1969	0207	±1	400	1139	1112–1165	960 ± 50		+2 to −2	+13	2
	Jan. 9, 1970	0716	±1	482	1164	968–1281	1000 ± 50		+0 to −7	0	4
	Jan. 19, 1970	0549	±1	422	1092	1049–1135	1000 ± 50			+1	2
	March 7, 1970	2355	±1	954	4585	3934–5296	3500	Extrapolation	−5 to 0	−1	4
Millstone	June 18, 1969	2306		625	2794	2794	2260		+2	−6	1
	June 19, 1969	0928	±1	425	2611	2427–2810	2520		+3 to −3	+2	3
	Nov. 20, 1969	1344	±1	970	3713	3682–3743	3900		+1 to −1	0	2
SRI	Feb. 20, 1970	0530	±40	570	2230	2022–2522	2250	2000–2500	+3 to −2	+10 to −15	6
Malvern	Oct. 22, 1969	0114	±1	480	1258	1123–1394	1300 ± 200		0 to −5	+11	2

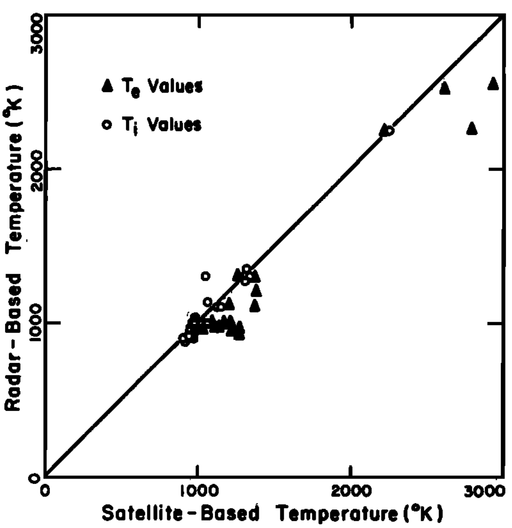

Fig. 3. Radar-based versus satellite-based T_e (triangles) and T_i (circles). The T_i measurements are in good agreement. The average satellite to radar temperature ratio $T_{eS}/T_{eR} = 1.15$. No simple empirical relation between T_{eS} and T_{eR} can adequately describe this data set. Note that two comparisons of $T_e > 3000$°K from Table 1 are not shown here.

The results presented here do not explain the persistent discrepancy between the probe- and the backscatter-measured electron temperatures. The number of available data points is too small for any statistical interpretation, but no specific trend can be detected. It is also apparent that no simple empirical relation between the probe and the radar data can describe the T_e results presented in Figure 3.

RPA. The Ogo 6 RPA is located on the forward-looking face of Opep 2 (Figure 1); its operation has been described in detail by *Hanson et al.* [1970]. A segment of data typical of results obtained outside the polar regions appears in Figure 4. Only every second RPA sweep is shown, except that, because of a data dropout, three sweeps are omitted between 42.1° and 44.6°N. Barring such problems, the sweeps not shown are generally of the same quality as the ones displayed. The corresponding theoretical current-voltage curves fit to the data points by a least-squares analysis program are also shown in the figure. The derived T_i values range from 964° to 982°K.

Such a small scatter in T_i ($\pm 1\%$ or better) is typical of the best Ogo 6 RPA data; however, there are many possible sources of systematic error, and without independent information (e.g., the radar comparisons discussed herein) it is difficult to place limits on the absolute accuracy of the T_i measurements, though the work of *Hanson et al.* [1972] and *Yadlowsky et al.* [1972] suggests that the absolute systematic errors should be <5%. Most of the possible errors would affect all the T_i values in approximately the same way, and thus the high internal precision of the data set permits an intercalibration of the incoherent scatter network independent of any systematic errors.

Figure 5 shows the T_i data of Figure 4 plus the T_e data of Figure 2 compared with data nearly coincident in time and space from the French (CNET) radar. The satellite- and radar-based T_i values agree well, but the Ogo T_e value is 155°K above the radar value (see also Table 1).

Table 2 contains primary information about the T_i comparisons. We tried insofar as possible to compare data obtained at the same dip lati-

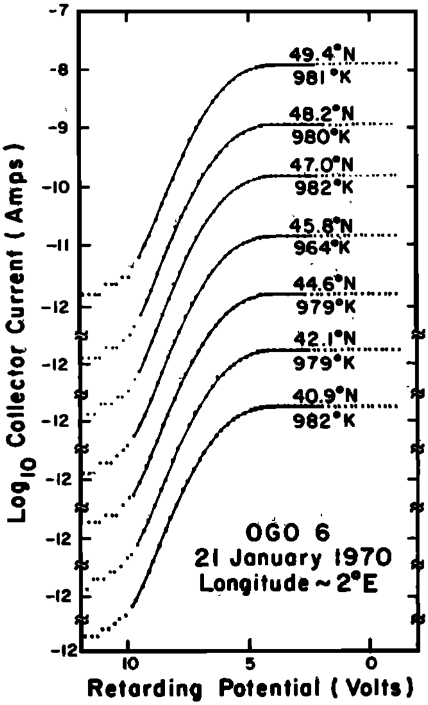

Fig. 4. An example of typical RPA data, corresponding to the radar satellite comparison illustrated in Figure 5. The geographic latitude is shown here as it is in Figure 2.

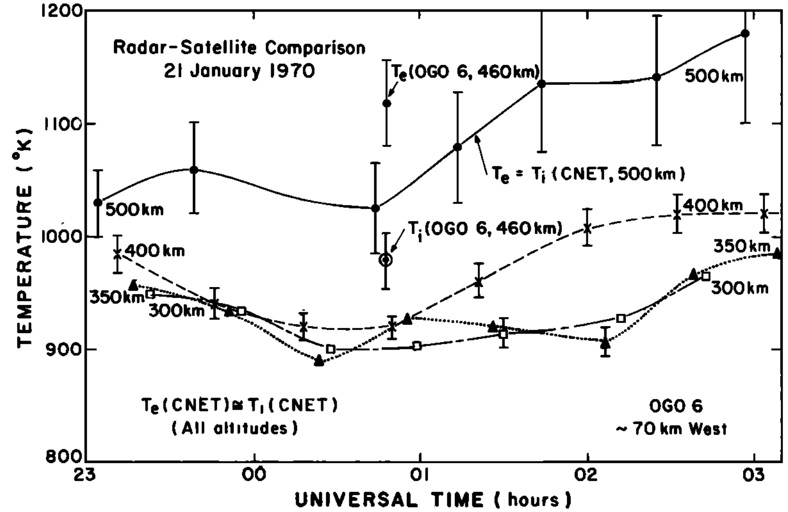

Fig. 5. A comparison of radar and satellite data. The raw satellite data and the corresponding best-fitting theoretical curves are illustrated in Figures 2 and 4. The CNET radar indicated $T_e = T_i$ approximately at all times and altitudes shown. The CNET and Ogo 6 data are labeled on the figure.

TABLE 2. Ion Temperature Comparisons

Station	Date UT	Altitude, km	Ground Track Distance, km E or W	LT, hr	T_i Ogo, °K	T_i Radar, °K
CNET	Oct. 22, 1969	503	440E	0202	980 ± 25	965 ± 25
	Nov. 13, 1969	430	2660W	2308	900 ± 50	910 ± 30
	Jan. 19, 1970	485	1040E	0119	980 ± 20	950 ± 35
	Jan. 21, 1970	460	70W	0040	980 ± 20	980 ± 20
	Jan. 22, 1970	446	1190W	0036	960 ± 20	950 ± 50
	Feb. 5, 1970	407	1060E	2238	865 ± 35	895 ± 30
	Feb. 17, 1970	505	990E 990W	2106	1130 ± 30	1100 ± 30
	Feb. 18, 1970	463	1140E	1008	1305 ± 30	1265 ± 20
Arecibo	Jan. 19, 1969	496	35W	0510	1130 ± 40	1065 ± 50
	Aug. 7, 1969	1070	190E	2245	1335 ± 20	1300 ± 150
	Oct. 10, 1969	836	690W	0309	1140 ± 50	1100 ± 110
	Nov. 13, 1969	400	1460E	0137	910 ± 40	960 ± 50
	Nov. 14, 1969	400	145W	0137	900 ± 35	970 ± 50
	Dec. 11, 1969	683	335E	1855	2250 ± 150	2250 ± 250
	Jan. 9, 1969	485	30E	0244	960 ± 30	960 ± 50
	Jan. 15, 1970	440	3740E	0236	1000 ± 20	1020 ± 50
	Jan. 16, 1970	424	360W	0237	1010 ± 20	990 ± 50
	Jan. 19, 1970	410	220E	0122	980 ± 50	1000 ± 50
	Feb. 5, 1970	455	175E	0003	990 ± 30	1035 ± 50
SRI	June 20, 1969	443	1200W	0502	1310 ± 50	1315 ± 60
Jicamarca	Nov. 1, 1969	620	240E	2351	1070 ± 40	1000 ± 50
	Nov. 14, 1969	446	525W	2220	880 ± 20	915 ± 20
	Nov. 16, 1969	445	140E	2210	940 ± 40	915 ± 20
Malvern	Oct. 22, 1969	475	885E	0212	1050 ± 50	1300 ± 200
	Feb. 18, 1970	442	1470E	1018	1310 ± 40	1350 ± 120

tude, local time, and altitude. Most of the data were obtained at night (because of the previously mentioned solar paddle difficulty) at times when there were no rapid local time variations of T_i. The ground track distance between the comparison points varied from 70 to over 2600 km. The larger distances were included in the comparison only when it was reasonable to expect, on the basis of both the satellite and the radar data, that T_i was very nearly equal to the neutral temperature T_n. In all cases there is agreement to within the tabulated uncertainties. These uncertainties represent only the statistical errors in the individual data sets and contain no allowance for the lack of a perfect temporal or geographical coincidence. Linear smoothing and interpolation in altitude and local time for the radar data and in latitude for the satellite data were used to find the final values of T_i and their uncertainties. Because of the high quality of most of the data used, little smoothing was required, but interpolation was often needed. The average temperature difference ($T_{iS} - T_{iR}$) is only +11°K for the CNET comparisons, −12°K for the Arecibo comparisons, and +20°K for the Jicamarca comparisons, these results indicating that no appreciable discrepancy exists between the two measurement techniques. As was previously noted, the systematic temperature differences are substantially smaller than the statistical uncertainties in the measurements themselves. Thus it appears highly unlikely that any unexpected sources of systematic error larger than a few percent are present in either measurement technique.

Typical radar data showing the altitude and local time variations of T_i are shown in Figures 6 and 7 along with nearly overlapping satellite T_i data. For the midlatitude (Figure 6) example it appears likely that T_i is nearly equal to T_n at the time and altitude of the Ogo 6 pass, although they are not equal at higher altitudes at the time of the pass or at the same and lower altitudes an hour before the pass. For the CNET comparison illustrated in Figures 4 and 5 it is clear that $T_i > T_n$ at the time and altitude of the satellite pass. On the other hand, at Jicamarca the nighttime behavior of T_e and T_i is such that one might expect T_i and T_n to be nearly equal below about 500 km, independent of altitude, at night, except under unusual circumstances [*McClure,* 1971]. The coincident Ogo 6 data of Figure 7 and of Table 1 are consistent with this interpretation. An interesting sidelight of the data of Figure 7 is that, although spread *F* extended to only 350 km at Jicamarca, 140 km east at the location of the satellite there were ionospheric irregularities, which were presumably 'spread *F*' irregularities, extending up to >455 km, the satellite altitude.

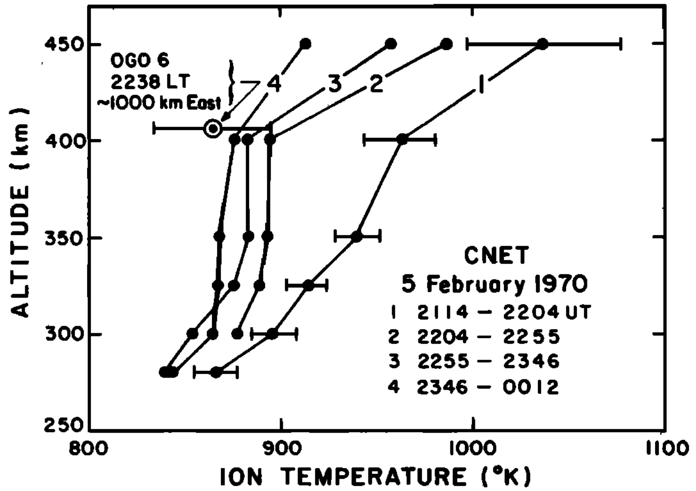

Fig. 6. Radar-based profiles of T_i and a corresponding T_i measurement from Ogo 6. Although the satellite was over 1000 km away, there was good T_i agreement. The error bars shown on profile 1 apply approximately for all four profiles.

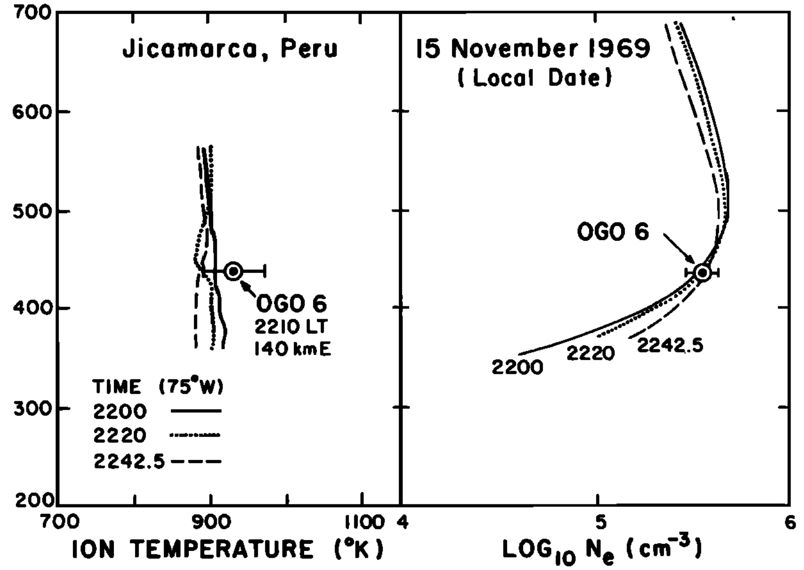

Fig. 7. A radar satellite comparison at Jicamarca. Spread *F* irregularities were observed at the satellite but only below 350 km at the longitude of the Jicamarca radar.

Conclusions. The RPA and radar values of T_i agree, on the average, to within less than the average of the statistical uncertainties of either of the separate data sets. Thus at least for these examples it appears very unlikely that either data set was affected by significant systematic errors. There are of course known sources of systematic errors for both radar and RPA measurements, but it would appear that presently used techniques can adequately account for such errors, at least under the circumstances of this comparison.

Our results do not offer any insight into the persistent T_e discrepancy between the probe and radar results. This discrepancy is less for the Ogo 6 instrument than that obtained for other cylindrical probes in previous comparisons of this kind. For example, the first such comparison [*Hanson et al.*, 1969] yielded a discrepancy of ~1.7 for data obtained at similar altitudes and local times. The bulk of the comparisons presented here, particularly those for the RPA, were obtained at relatively low temperatures at night. It is not known whether such good agreement would also be obtained for the much higher temperatures often encountered in the daytime or for the larger fractional abundances of light ions often encountered at night and/or at higher altitudes.

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