Local and Transcontinental Mapping of Total Electron Content Measurements of the Earth's Ionosphere

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The interchangeability of total electron content data for the purpose of ionospheric calibration of deep space radio metric data, both locally and across the North American Continent, is demonstrated. Comparisons were made between calibrations produced from Faraday rotation data recorded at Stanford and Goldstone in California and at Hamilton in Massachusetts for simulated missions to Mars. The results, in terms of equivalent station location errors, are shown. The averages of the differences between the tracking station spin radius errors are below one meter with standard deviations of about one meter for both data sources. The averages of the differences of ionospheric effect on longitude changes are also less than one meter with uncertainties of two to three meters. Transcontinental mapping of Faraday rotation measurements is concluded to be a competitive calibration scheme with local mapping. However, because of the large scatter in the longitude changes, the improvement in this coordinate using the electron data from another station is at best marginal.

The geomagnetic latitude factor used in the mapping is also investigated. This factor is found essential to the mapping procedure.

I. Introduction

The significance of the effect of charged particles in the ionosphere on navigation and especially on Deep Space Station location solution in post flight analysis has been amply demonstrated (Refs. 1 and 2). Ionospheric calibrations for post flight analysis are computed by the program HYPERION, which is a modification of the program ION (Ref. 3). This program takes the daily variation of the total electron content (TEC) as input and also calculates the line of sight of the deep space probe. The zenith TEC is then mapped, translated in time and space to the probe line of sight (Ref. 3). In addition, a geomagnetic factor which provides an adjustment to the differences in the geomagnetic latitudes between the stations is applied.

There are occasions when the electron calibration data needed for a particular mission or tracking station are not readily available. A possible solution would be to use the electron content data from another station for the calibration of these tracking data. This article discusses the resultant accuracy when this technique is applied between distant stations. The approach is to make comparisons between calibrations converted to equivalent station location errors for the same station using different sets of TEC data. The equivalent station location errors are changes in the apparent location of the tracking station due, in this case, to ionospheric effects. The changes in range and range rate caused by the group velocity delay and phase velocity decrease of the electromagnetic radiation through the ionosphere are converted to the changes in station spin radius and longitude through the Hamilton–Melbourne equation (Ref. 4). The tracking station used in these comparisons is DSS 14 with the TEC data measured at Goldstone and Stanford[1] in California during July and early August 1969 and Goldstone[2] and Hamilton[3] in Massachusetts gathered in July, August, and September 1971. The co-ordinates of the ionospheric reference points (Ref. 3) for these stations (350 km above sea level) are as shown in Table 1. The agreements between these calibrations would then indicate that the ionospheric data from any one of these stations can be used, if the errors revealed by these comparisons are acceptable.

The applications of the results of these investigations are:

(1) The potential improvement of the station location solutions for post-flight analysis when ionospheric calibrations are included.

(2) In flight calibrations for future missions could also be improved with TEC data from other stations.

(3) The extent of the interchangeability of the iono-sphere (in relation to its effects on transmitted signals) above different locations is of significant interest in VLBI (Ref. 5).

II. The Geomagnetic Factor

At first, comparisons of the daily zenith TEC diurnal variation were made to decide whether the calibration data from one station could be used to correct the tracking data of the other. The Stanford and Massachusetts daily TECs were mapped to the Goldstone zenith and the mapped and unmapped distributions compared. Although these distributions have roughly the same general shape (Figs. 1 and 2), finer features are different enough that a quick conclusion cannot be drawn. It was then thought that the geomagnetic latitude adjustment factor entering the mapping procedure (Ref. 3) might be caus-ing the discrepancies. To check this point, a month of the Hamilton electron content data has been mapped to Goldstone with this magnetic factor turned off. The dif-ferences between the two distributions became worse than before. Whereas the average of the daily differences with this factor included is 0.05×10^{17} electrons/m^2 ($\sim$0.07 m of radio path change at S-band) for this month, the corresponding average with this factor omitted is 0.38×10^{17} electrons/m^2. This magnetic adjustment fac-tor, therefore, is essential to this mapping procedure. Further analysis on the value of this factor will be per-formed to minimize as much as possible the average of the daily differences.

III. Local Mapping of TEC

Miller and Mulhall (Ref. 6) have shown the accuracy of local mapping in winter to be about 0.11×10^{17} electrons/m^2 between the TEC along the lines of sight of ATS-1 and ATS-5 from Goldstone. To further the analysis, comparisons were carried out with the Stanford and Goldstone TEC data for a *Mariner 6* flight in 1969 tracked by DSS 14. The station location changes thus obtained in July are given in Figs. 3 and 4 for the re-spective ionospheric calibrations. The monthly averages for these changes are given in Table 2. The differences of these changes (Goldstone–Stanford) are shown in Fig. 5. The average of these differences for July and that for the few days in August are shown in Table 3. The large standard deviation in the average of the spin radius errors in July is greatly influenced by the anomalous point of July 17. If this point is omitted, the average becomes 0.41 ± 0.70 meter.

IV. Transcontinental Mapping of TEC

To test the validity of transcontinental mapping, a similar comparison was made for two and a half months of data between Hamilton and Goldstone. A Mars mis-

sion has been assumed and the *Mariner* Mars 1969 encounter view period has been simulated in the year 1971, since the ionospheric data for the *Mariner* Mars 1971 encounter was not available. Calibrations were computed using both the ionospheric electron data from California and Massachusetts. The spin radius and longitude changes obtained in July for these two data sets are shown in Figs. 6 and 7 as typical examples. Table 2 also gives the monthly averages of these changes.

Figure 8 shows the differences between the equivalent station location changes using the California and Massachusetts electron content data for July. The monthly averages of these differences are given in Table 3. The larger differences in the spin radius changes between California and Massachusetts in September are not only influenced by the anomalous point on September 4 but also by the smaller size of the data sample involved.

V. Conclusion

The results obtained from these comparisons show a very interesting and encouraging fact. It is interesting that the mapping of the Massachusetts ionospheric TEC data to Goldstone for the station spin radius errors is as good as the mapping of the Stanford data to Goldstone. No such conclusion, however, can be drawn for the station longitude errors. Although similar cases about the degradation of the longitude solution with ionospheric cali-

bration have been observed (Ref. 1), no explanation is yet available. In any case, whether such a calibration should be applied to the longitude solution has yet to be decided. However, despite the large longitude difference, as shown in Table 1, the mapping of the Massachusetts data is in close competition with the local mapping for the spin radius solution. This is very encouraging indeed since without the ionospheric calibration the spin radius is about four meters off, while with the calibration using the TEC from another station, this error is cut to the one-meter level. It can be concluded that ionospheric calibrations for in-flight operation or post-flight analysis are a significant improvement in Δr_s (and at best marginally in $\Delta\lambda$) when the calibration data are available locally. Moreover, this is also true when the data from a remote station are being used. These improvements come close to the goals for *Mariner* Venus–Mercury 1973 based on mission specifications (Project Document 615-10) that charged-particle error in change in path length over a pass of 1.0 m (1 σ) is allowable. The significance of these ionospheric investigations to VLBI will be presented in another paper (Ref. 7) in the near future.

VI. Future Analysis

Further analysis will be performed among stations all over the world to check the validity of ionospheric mapping on a global scale and improve on the accuracies of the objectives set forward in this article.

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Table 1. Coordinates of ionospheric reference points

Station	Geostationary satellite	Latitude, deg	Longitude, deg
Goldstone	ATS-1	32.6	239.5
Stanford	ATS-1	34.2	234.38
Hamilton	ATS-3	39.3	289.2

Table 2. Monthly average of station location changes

TEC source		Δr_s, meter			$\Delta\lambda$, meter		
		July	August	September	July	August	September
1969	Goldstone	4.33 ± 1.33 (26)[a]	4.36 ± 0.78 (6)		1.52 ± 2.25	3.42 ± 2.47	
	Stanford	3.86 ± 1.08 (31)	4.42 ± 0.91 (6)		0.48 ± 2.73	3.08 ± 2.27	
1971	Goldstone	4.40 ± 0.90 (21)	3.77 ± 0.73 (29)	4.06 ± 1.42 (14)	0.35 ± 2.03	0.08 ± 2.43	0.66 ± 2.52
	Hamilton	4.49 ± 0.72 (25)	3.79 ± 0.65 (31)	3.35 ± 0.69 (16)	-1.11 ± 1.80	-0.22 ± 1.80	1.15 ± 1.06

[a]Number of points included in sample.

Table 3. Monthly average of the differences in station location changes

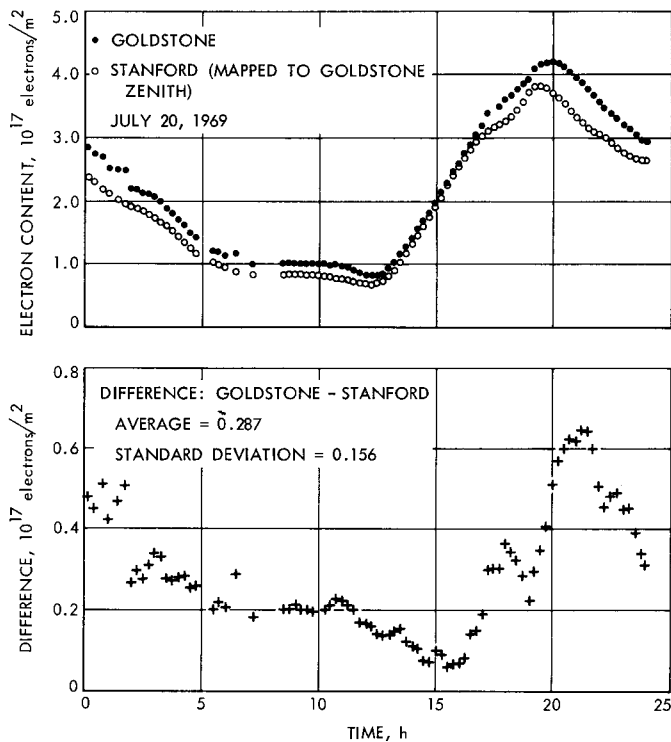| TEC sources differenced		$\Delta r_{s1} - \Delta r_{s2}$, meter			$\Delta\lambda_1 - \Delta\lambda_2$, meter		
		July	August	September	July	August	September
1969	(1) Goldstone (2) Stanford	0.63 ± 1.26	-0.29 ± 0.41		0.68 ± 2.58	0.55 ± 3.24	
1971	(1) Goldstone (2) Hamilton	-0.21 ± 0.96	-0.06 ± 0.98	0.75 ± 1.74	0.99 ± 2.41	0.41 ± 3.24	-0.45 ± 2.35

Fig. 1. Typical diurnal variations of the zenith TEC
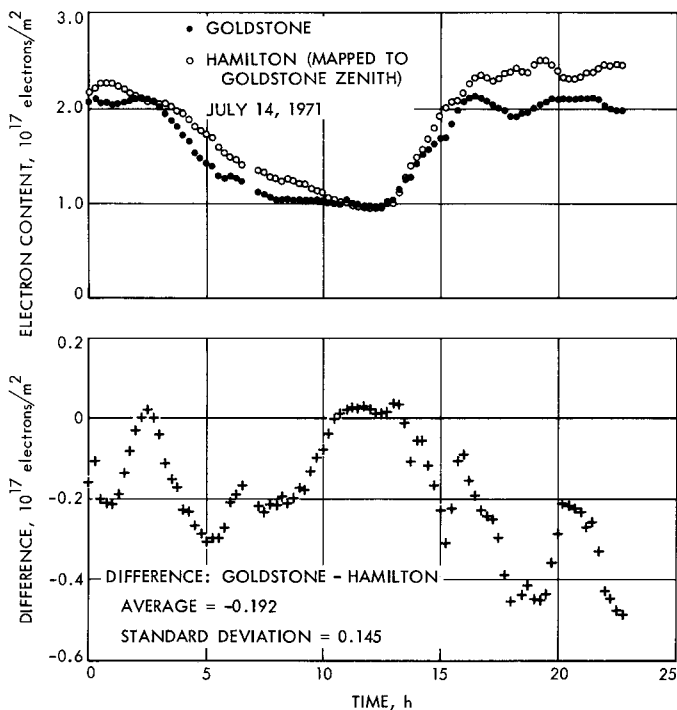at Goldstone and Stanford

Fig. 2. Typical diurnal variations of the zenith TEC
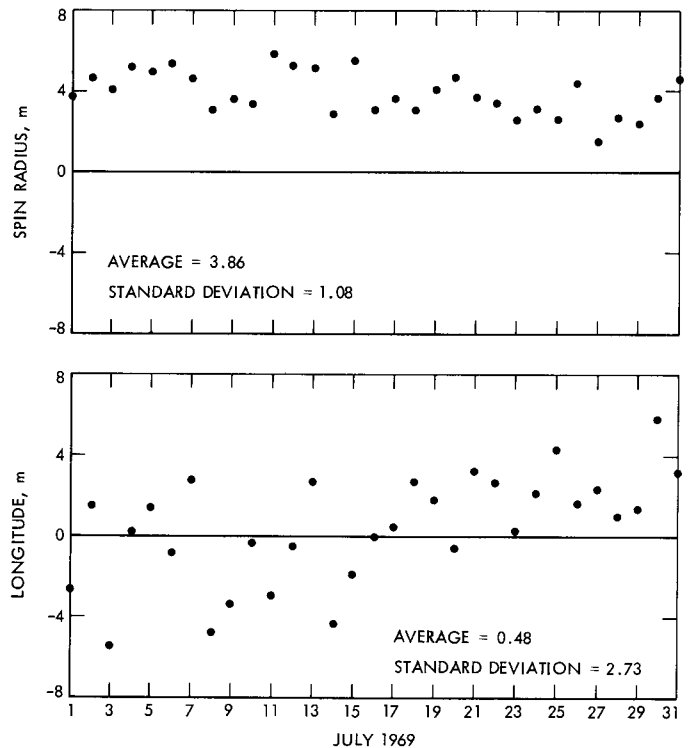at Goldstone and Hamilton

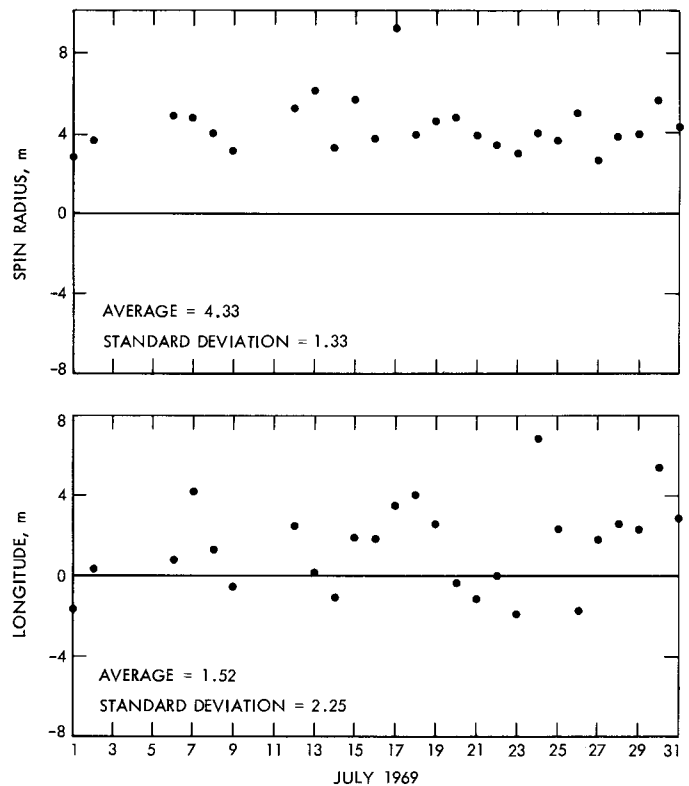Fig. 3. Station location changes for *Mariner* 6
(Stanford TEC)

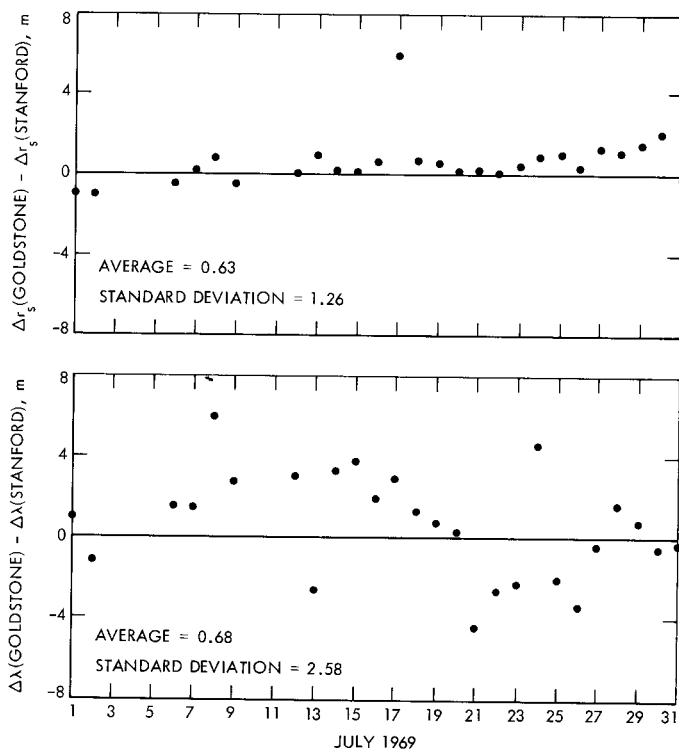Fig. 4. Station location changes for *Mariner* 6
(Goldstone TEC)

Fig. 5. Difference between station location changes:
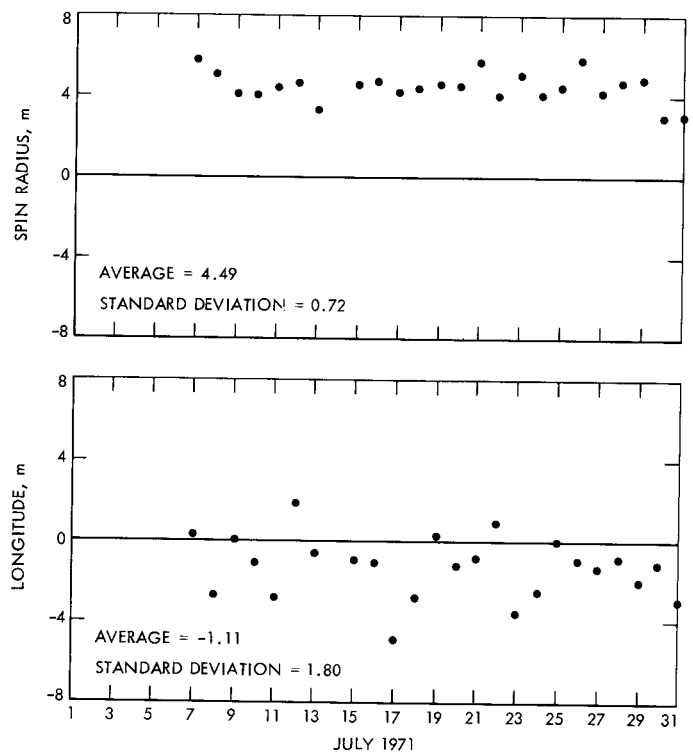(Goldstone — Stanford)

Fig. 6. Station location changes for *Mariner* 6 in 1971
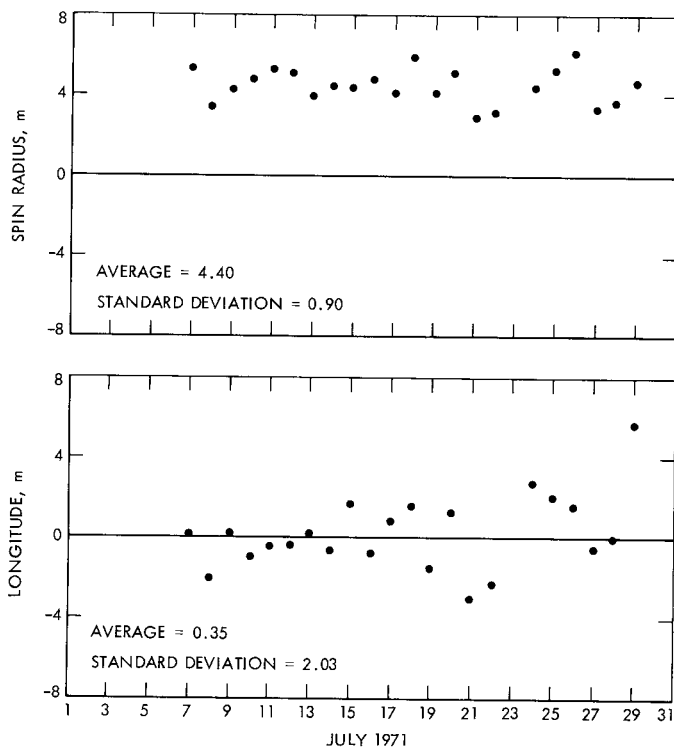(Goldstone TEC)

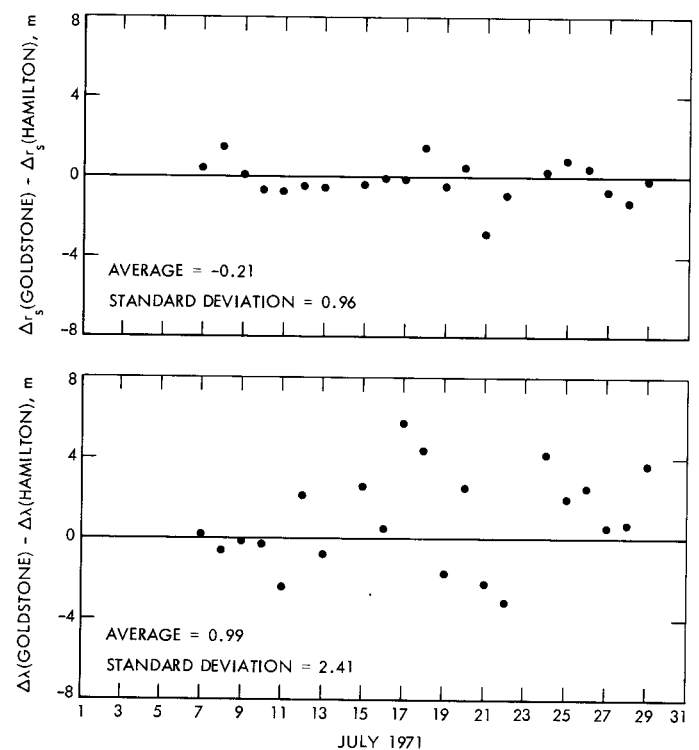Fig. 7. Station location changes for *Mariner* 6 in 1971
(Hamilton TEC)

Fig. 8. Difference between station location changes
(Goldston — Hamilton) for *Mariner* 6 in 1971