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Equatorial Ionospheric Irregularities Produced by the Brazilian Ionospheric Modification Experiment (BIME)

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On two separate evenings in September 1982, rockets were launched into the bottomside equatorial F_2 region off the coast of Natal, Brazil, to inject chemicals, consisting of mainly H_2O and CO_2, to create a hole in ionization. The chemicals were injected near the height where the density gradient was steepest, and at a time when the F_2 region was rising rapidly, to see whether plasma bubble irregularities could be generated from instabilities triggered by the ionization hole. On both occasions, hole-induced depletions in total electron content (TEC) of more than 10^{16} el/m^2 were observed over horizontal distances of at least 60 km from the chemical injection point. The eastward drifts of these artificial depletions were observed by the time difference in the TEC features observed at various TEC monitoring stations, and from the changing range of oblique ionosonde echoes observed by an ionosonde located 300 km magnetically east of the chemical release point. Their subsequent evolution into plasma bubble irregularities was demonstrated from the observations of spread F echoes, strong-amplitude scintillation, and TEC depletion at distances of from 300 to 500 km eastward of the release points. The fact that similar behavior of the ionosphere was observed during the evenings of both rocket chemical releases, and on no other nights of the campaign, is strong evidence of successful artificial generation of bubble irregularities by chemical injection into the bottomside F_2 region.

INTRODUCTION

One of the major questions in ionospheric research on the low latitudes concerns the generation of plasma bubbles [*McClure et al.*, 1977] in the bottomside ionosphere that subsequently rise through h_{max} [*Woodman and La Hoz*, 1976], producing a hierarchy of smaller-scale irregularities associated with it [*Haerendel*, 1973]. Coherent returns from 3-m scale size irregularities, extending up to approximately 1000 km in height, have been mapped as plumes by the 50-MHz radar over Jicamarca [*Woodman and La Hoz*, 1976]. Amplitude scintillation measurements of kilometer-scale size irregularities have been reported by numerous workers (see reviews by *Basu and Kelley* [1979] and by *Basu and Basu* [1985], and references therein). The west to east velocity of bubble irregularities has been measured by the spaced receiver technique by *Abdu et al.* [1985, 1983*b*], and by *Yeh et al.* [1981]. The association of scintillation with depletions in TEC has been described by *Tyagi et al.* [1982].

Theoretical modeling of the generation of a vertically rising plasma bubble, starting from an initial perturbation introduced at the height where the bottomside gradient of the F region was steepest, was first done on the basis of the Rayleigh-Taylor fluid instability mechanism by *Scannapieco and Ossakow* [1976]. Experimental verification of the upwelling of natural depleted density regions during spread F produced by the Rayleigh-Taylor mechanism has been reported from rocket and radar measurements conducted over Natal by *Kelley et al.* [1976]. *Anderson et al.* [1982] proposed that internal gravity waves, generated in situ from wind shear, also could be a possible seeding mechanism for equatorial spread F.

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A combined Brazilian-United States effort, called the Brazilian Ionospheric Modification Experiment (BIME) [*Narcisi*, 1983], was the first experimental attempt to create an artificial perturbation in the bottomside of the equatorial F_2 region to verify if an instability process leading to plasma bubble generation could thereby be initiated. Explosive chemical releases, containing mostly water vapor and CO_2, were conducted on two separate nights to create a hole in the bottomside ionization where the gradient was steepest, and when the height of the ionosphere was rising rapidly, in hopes that this artificial hole would rise through the more dense background ionosphere and stimulate the creation of a large-scale plasma depletion with its associated irregularities.

A network of stations was set up near Natal, Brazil, in September 1982 to measure transionospheric propagation effects of changes induced in the ionosphere by chemical releases from rockets. Our stations were set up to monitor Faraday polarization changes, proportional to total electron content (TEC), and amplitude scintillations from the geostationary satellite Sirio, conveniently located eastward of Natal, so that the ray paths from the satellite to the various stations would pass near the chemical release point. A Faraday polarization monitoring receiver (polarimeter) was also set up on the island of Fernando de Noronha (FN), located 300 km magnetically eastward of the chemical release point, to observe the far eastward progression of the hole-induced disturbance and development of plasma bubble irregularities triggered in the process, as evidenced by the amplitude scintillations and TEC depletion observed by the polarimeter. An ionosonde was also located on FN.

Figure 1 shows the locations of stations near Natal and the points where straight line rays from Sirio through the center of the two BIME chemical releases are projected onto the Earth's surface. Also shown in Figure 1 is the location of the island of FN relative to Natal. Note that FN is located on

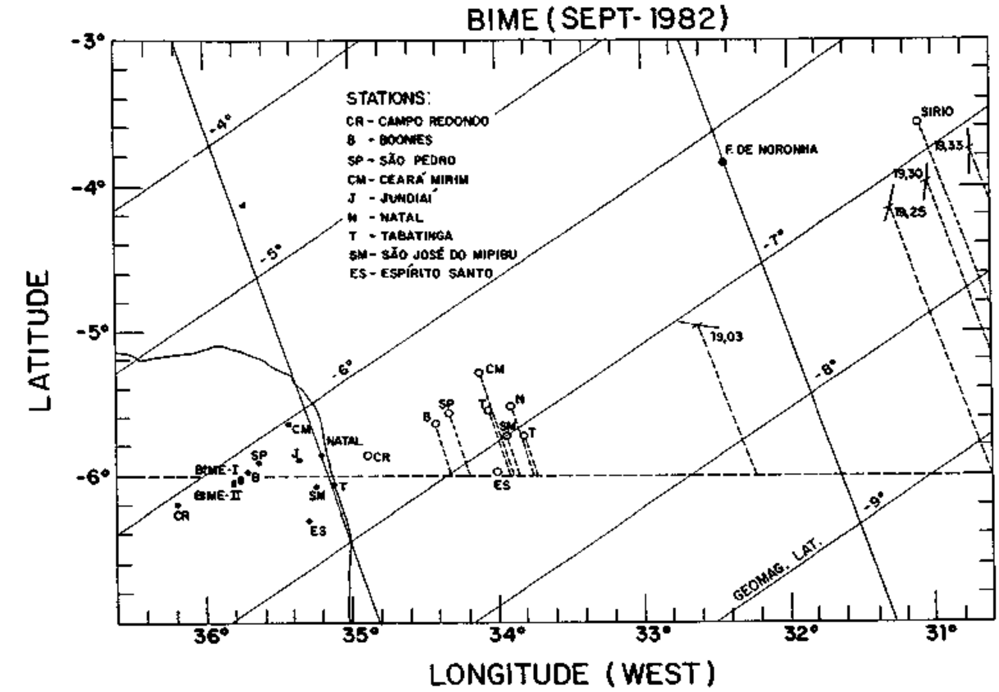

Fig. 1. Location of Sirio satellite receiving stations and projection of lines from the Sirio satellite through chemical releases for BIME-1 and BIME-2 to the surface. The open circles are the ground projection of the ionospheric intersection of the polarimeter ray paths to the Sirio satellite. Also shown is the Island of Fernando de Noronha located off the coast of Brazil.

nearly the same magnetic latitude as Natal. The polarimeter stations were located along two lines, approximately along a north-south line of equal magnetic longitude and along an east-west line of nearly equal magnetic latitude. Figure 2 shows the rays from Sirio to the various stations located near Natal, along with the locations of BIME-1 and BIME-2, the two separate, nearly identical, experimental chemical releases.

RESULTS: BIME-1

For BIME-1 we tried to locate one station so that the ray from Sirio would pass as closely as possible to the center of the hole to attempt to measure any focusing of the VHF ray. While previous experiments have shown a focusing effect due to the steep gradients created by an artificial hole (J. R. Clynch, private communication, 1977, and J. L. Baumgardner, private communication, 1979), we saw no amplitude focusing for either of the two BIME chemical releases. Our sensitivity to amplitude changes from the 136-MHz signal from the Sirio satellite was approximately 0.3 dB.

To determine why we did not see any evidence of ray focusing from the chemical releases, we took the measured values of maximum TEC depletions from both the BIME-1 and the BIME-2 chemical releases, used various assumed spherical and cylindrical shapes of electron density gradients, and found that the maximum focusing we could obtain was still less than 0.1 dB. The BIME chemical releases were placed significantly below the height of the F region maximum, at a point where the bottomside gradient was already high. After not measuring any amplitude changes, or even being able to compute a significant amount of focusing from the range of gradients likely produced by the BIME chemical releases, we looked further into the previous reports of VHF amplitude focusing. The focusing reported by J. R. Clynch (private communication, 1977) occurred for a chemical release near the peak of the F region, during much lower background ionospheric conditions, and resulted in much larger gradients than the BIME cases. The focusing observed by J. L. Baumgardner (private communication, 1979) was from an electron density depletion from chemicals released by a large rocket launch of a satellite where the total number of molecules released in the F region, and hence the electron density depletion, was much greater than in the BIME experiments. Further, both of those reports of VHF amplitude focusing were made from satellite VHF signals monitored at lower elevation angles with significantly greater distances from the larger gradients produced, thereby also allowing the rays to focus more.

We did measure decreases in TEC for both BIME-1 and BIME-2 at our polarimeter stations. The decreases in TEC were obtained by fitting least squares, higher-order polynomials through the background changes in TEC for each station to obtain a smooth curve for the portion of the evening during the event, and then subtracting this smooth curve from the actual TEC observed at each station. The maximum TEC decrease observed at each station for both the BIME-1 and BIME-2 chemical releases is illustrated in Figure 3. Note that a TEC decrease of almost 2×10^{16} el/m^2 was observed up to at least 60 km away from the chemical release point. For BIME-1 we had no station located west of the chemical injection point.

By the time that the depletion due to the chemical release reached the vicinity of the island of FN, it was a fully developed plasma bubble irregularity structure, as evidenced by oblique echoes observed from the vertical incidence ionosonde located there. On the FN ionograms, so-called "satellite traces," adjacent to the main F layer trace, were detected following both the BIME-1 and BIME-2 release experiments. Their displacements relative to the main F layer trace in the successive ionograms were consistent with an eastward drift of

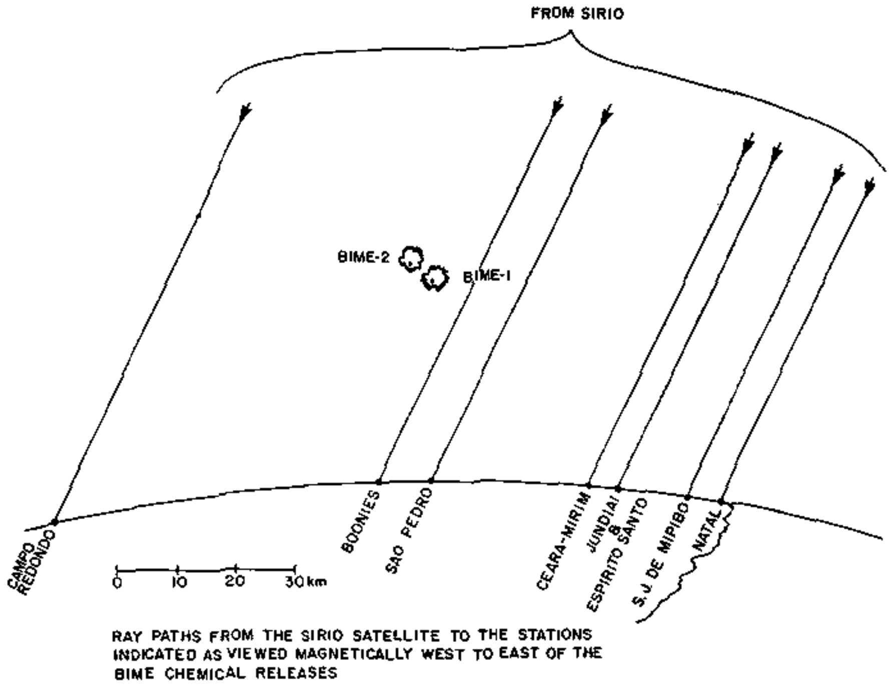

Fig. 2. Ray paths from the SIRIO satellite to the stations indicated as viewed magnetically west to east of the BIME chemical releases.

the disturbance from the release point. These traces got progressively diffused into range-type spread F echoes as they drifted past the meridian of the ionosonde located on FN.

In order to determine the approximate distance from the ionosonde station where the ionogram satellite traces originate, we have assumed that the ionosonde reflections arise from field-aligned structures such that the reflection points are always located very close to the magnetic latitude of 7.2° south latitude. The dip latitude of FN is 6.2° south. The group retardation factor used for obtaining the real range from the ionograms was 30 km in the vertical, as obtained from comparing the BIME rocket electron density profile [*Trzcinski and Narcisi*, 1983] with simultaneous ionograms over Natal [*Reinisch and Buchau*, 1983].

The BIME-1 chemical release took place at 1845:24 LT, and the FN ionosonde detected satellite traces, presumably approaching from the west, starting from 1905 LT 45° west. The ionogram at 1920 LT marked the near merging of the diffusing trace with that of the main F layer and represented the closest approach of the disturbance to the station. The ionogram satellite trace got progressively diffused into spread F echoes in successive ionograms. The horizontal distances of the field-aligned disturbances were determined from successive ionograms and then were projected along the magnetic meridian onto a reference geographic latitude of 6° south, as illustrated in Figure 1.

The results of these projections of the ionosonde satellite traces, as well as the times of the electron content depletions observed from the polarimeter network located on the mainland near Natal, are shown, as a function of local time, in Figure 4. The successive positions of ionosonde oblique echoes in the FN ionograms are marked by solid triangles, while the scintillation onset is marked by horizontal lines, with the length of the line indicating the relative intensity of the scintillations. The uncertainty of the location of the oblique echo near 31.2° occurs due to the difficulty in determining the echo reflection point location when it occurs near the magnetic meridional plane of the station. A subionospheric height of 320 km has been used for the weak scintillation onset at 1920 LT, which was most likely associated with a bottomside spread F irregularity patch that was present over FN during these times.

As the chemically induced hole in ionization moved east-

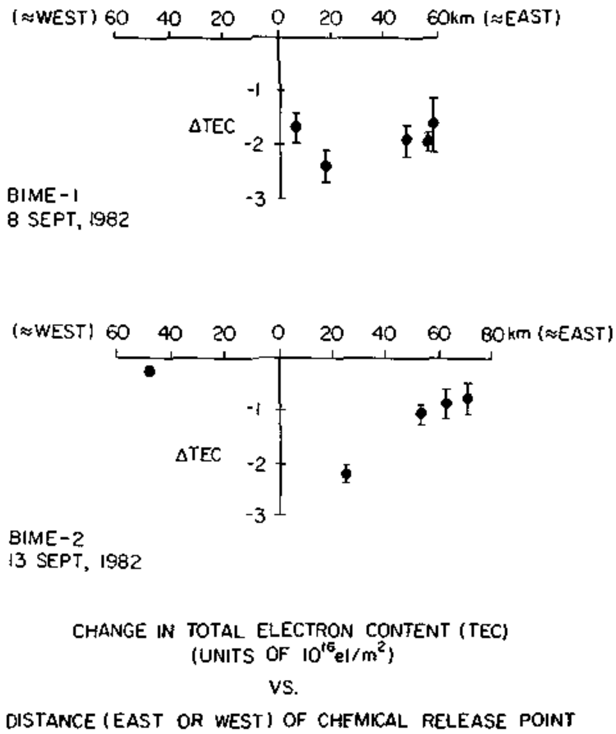

Fig. 3. Summary of TEC decreases observed for both BIME chemical releases versus distance from the chemical release point.

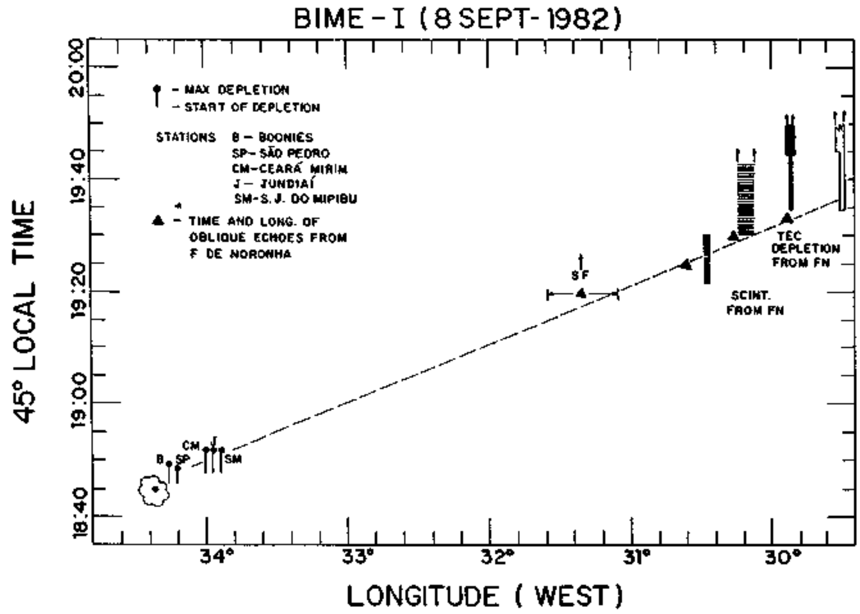

Fig. 4. Local time versus longitude of the TEC depletions produced by the BIME-1 chemical release observed by the polarimeter chain located in the vicinity of Natal, extended to the observations made by the ionosonde and polarimeter located at Fernando de Noronha.

ward, a much larger depletion in TEC, with associated irregularities as seen by strong scintillations and spread *F*, was observed from FN. This enhancement in the scintillation, that had its onset starting from 1930 LT has been plotted for a subionospheric height of 420 km, consistent with the height of the diffusing satellite traces in the ionogram at this time. The associated bubble depletion onset over FN at 1934 LT, and its subsequent enhancement at around 1945 LT, are marked for a subionospheric height of 520 km (solid patch), and for purposes of comparison, also for a subionospheric height of 620 km. A maximum TEC depletion of approximately 5×10^{16} el/m^2 column was observed from FN, more than twice the maximum TEC depletion directly produced by the BIME-1 chemical release. The mean velocity of propagation in the magnetically eastward direction, obtained from the analysis shown in Figure 4, was approximately 170 m/s.

Approximately 15 min elapsed from the time the TEC depletion (hole) was observed near Natal until the first oblique echo was observed from the FN ionosphere. During that time the eastward mean velocity of approximately 170 m/s carried the developing bubble some 230 km eastward of the chemical release point. It continued at approximately the same velocity eastward until it was last seen by the presence of ionogram oblique echoes from FN at 1933 LT, by which time it was nearly 500 km geographically east (namely, 460 km magnetically east) of the chemical release point.

RESULTS: BIME-2

For the BIME-2 chemical release we did not attempt to locate a polarimeter directly at the ground intersection of the straight line from the Sirio satellite through the planned chemical release point. Instead, one of the polarimeters was moved to a location approximately 50 km west of the chemical release point to attempt to determine if there would be any difference in the east-west chemical hole shape, or if the hole could be seen to move first in a westward direction as had been postulated by G. Haerendel (private communication, 1982). We saw no direct evidence of a westward movement of the chemically produced hole, but we did observe an east-west asymmetry in the hole shape as shown in the lower portion of Figure 3. Note that in Figure 3, the one measurement located west of the hole for BIME-2 observed a much smaller TEC depletion than measurements from the same, or greater, distances to the east of the chemical deposition point.

Ionosonde oblique echoes were again observed from FN for the BIME-2 event. The chemical release took place at 1808:32 LT and the ionogram satellite traces that were received, starting from 1850 LT, were assumed to be evidence of an eastward propagating disturbance. Figure 5 illustrates the times of observation of depletions and scintillation from the various polarimeter stations, as well as the times and locations of ionosonde oblique echoes for the BIME-2 event. The polarimeter on FN was monitoring VHF signals from the GOES-1 satellite during the period of the BIME-2 event, and the ionospheric intersection of the path to the GOES-1 satellite was westward of the chemical release point. Thus no effects from the BIME-2 chemical release were seen on the polarimeter located on FN.

The propagation time of the disturbance from the chemical release point to the magnetic meridian of FN corresponds to an average velocity in the magnetically eastward direction of 145 m/s. From the time of the initial observation of the chemically induced depletion to its observation as ionosonde oblique echoes near FN, its eastward velocity speeded up from approximately 145 m/s to over 300 m/s.

The evidence from the BIME-2 chemical release also clearly shows that irregularities were produced by the chemical release, not at the location of the chemical release, but eastward of that location, by which time they had an opportunity to fully develop. The time between the chemical release and the subsequent first observation of strong oblique spread *F* echoes from the Fernando de Noronha ionosonde was approximately 41 min. The projected distance eastward of the chemical release point to where the spread *F* was first observed was approximately 300 km.

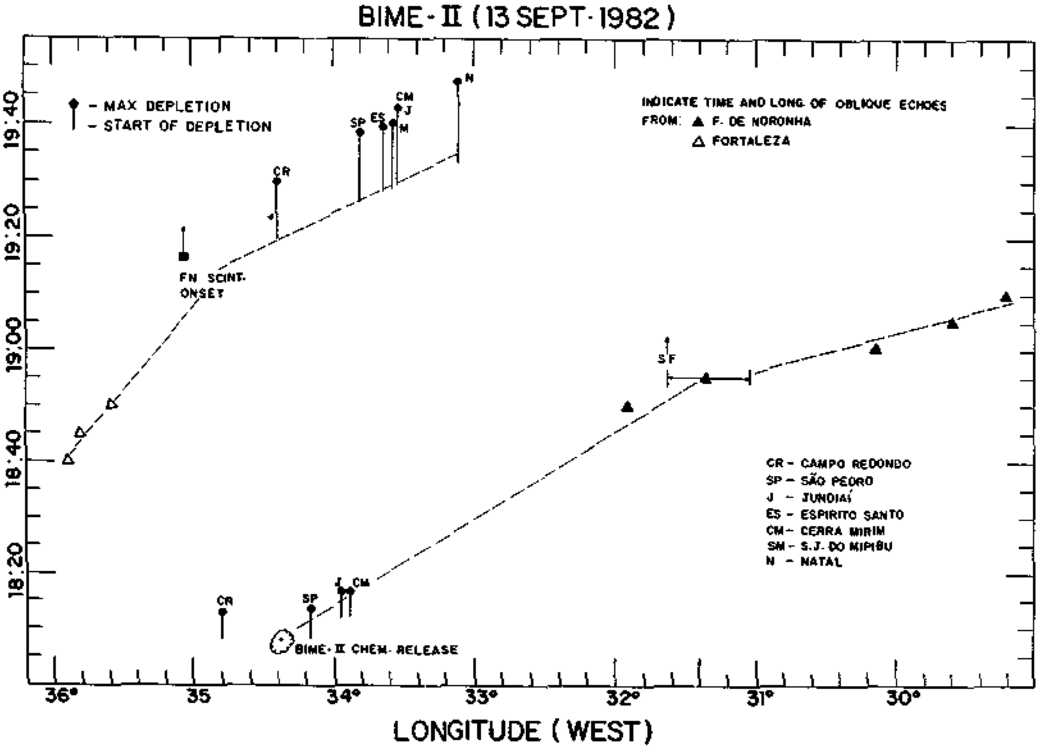

Fig. 5. Local time versus longitude of the TEC depletions and ionogram oblique echo locations for the BIME-2 chemical release plotted in a similar way as for BIME-1.

Figure 5 also shows a natural depletion in ionization which was observed later on the night of the BIME-2 event. This depletion was observed first as oblique ionogram echoes on the Fortaleza ionosonde, located to the northwest of Natal, then on the ray path from the GOES-1 satellite monitored from Fernando de Noronha, and later at the various polarimeter stations located near Natal. The progression of this natural disturbance is illustrated on the upper left hand side of Figure 5, where oblique ionogram traces corresponding to this natural spread *F* event are indicated by the open triangles. Also shown in the left hand, increasing time scale of Figure 5, are the onset times indicated by the bottom edge of the vertical lines for each polarimeter station. The time of maximum depletion is indicated by the solid circles. The velocity of the natural depletion observed on this night also was observed to increase during its eastward motion. This is clearly seen as a change in slope in the upper (later time) portion of Figure 5.

DISCUSSION AND CONCLUSIONS

The ground-based diagnostic network operated during the BIME campaign has permitted rather detailed diagnostics of the chemically induced ionization holes and their subsequent eastward drift and evolution into plasma bubble irregularities. These diagnostics involved the determination of the depletion magnitude at the hole centers, the sizes of the holes, and their evolution in the ambient ionosphere. The velocities of the holes calculated from the polarimeter observations substantially agreed, in the one instance where a comparison could be made, with those of the neutral wind as determined by a Fabry-Perot interferometer [*Biondi and Sipler*, 1985]. During approximately the first 7 min from the releases the polarimeters near Natal monitored the eastward drift of the holes up to some 60 km from the release point, during which no bubble growth was detected. The evolution of these holes into spread *F* irregularities, which did occur subsequently, as detected by the FN ionosonde close to and westward of the FN magnetic meridian, took approximately 35 min from the release times, both for the BIME-1 and the BIME-2 experiments. Further evolution into bubble irregularities occurred above and eastward of the FN meridian when scintillation (10 dB) and a TEC depletion (5 TEC units) were detected by the FN polarimeter during BIME-1 in reasonable agreement, also, with the irregularity structure locations determined from the FN ionosonde.

Thus the evidence obtained from the network of polarimeters located in the vicinity of Natal, and the polarimeter and ionosonde on the island of FN, located some 300 km magnetically east of Natal, clearly showed that chemical depositions into the bottomside ledge of a vertically rising *F* region, on two separate evenings in September 1982, did initiate instability processes that grew into fully developed depletions of ionization. Although both the spread *F* and plasma depletion were measured during the BIME-1 experiment, the absence of polarimeter diagnostics at FN during the BIME-2 experiment permitted only the spread *F* observation from that location. We did not observe depletions or scintillations at such early times on any other evening during the BIME campaign period in September as we did on the evenings of the two chemical releases.

The ionogram signatures of the spread *F* evolution that followed the BIME chemical releases on the two evenings were distinctly different from those of natural spread *F* events, in that they had their initiation starting from the higher-frequency band (range) in the ionograms, whereas the natural events (as seen over Fortaleza, and on some days of the BIME campaign period, over FN) always developed from the lower frequency end of the ionogram (*Narcisi* [1983]; see also *Abdu et al.* [1983*a*]). This signifies higher reflection heights for the initial disturbances that preceded the spread *F* events in the BIME experiments as compared to the lower altitudes (*F* region base), where precursor disturbances are usually seen in the case of natural events. These distinctly different spread *F* development signatures thus provide additional evidence of the successful triggering of the bubble irregularities during both of the BIME experiments.

The chemical stimulation of an instability in the bottomside equatorial *F* region should be attempted again, with additional appropriate diagnostics located sufficiently far eastward of the chemical deposition point to insure the continuous monitoring of the eastward zonal drift and evolutionary phases of the plasma bubble irregularities that could develop from an initial electron density perturbation.

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