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14. Abstract/Notes

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VAPOUR CLOUD INDUCED PLASMA BUBBLE IRREGULARITY GROWTH AND DYNAMICS IN THE EQUATORIAL IONOSPHERE

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ABSTRACT

With the objective to test the current theories on the ambient ionospheric conditions and triggering sources responsible for equatorial spread F phenomenon, two ionospheric modification experiments were conducted on consecutive evenings of September 17 and 18, 1982 from Natal, Brazil, in which two SONDA III rockets were used to inject Barium and Europium clouds at the steep bottomside ledge of a stable, but rising, twilight equatorial F-region, in an attempt to initiate development of plasma bubble irregularities. The eastward drifts of the bigger clouds at higher levels that were tracked by optical triangulation method in the sunlit side of the terminator was followed up in the shadow region by radio diagnostic instruments, consisting of a digisonde at Natal, airborne UHF scintillation receivers, and an ionosonde and a VHF electronic polarimeter at Fernando de Noronha, ~400 km eastward of Natal. The results from these different diagnostic techniques provide evidence that the modification experiment did succeed in producing vertically rising plasma bubble irregularities in the vicinity of the eastward drifting cloud induced perturbations.

1- INTRODUCTION

Equatorial ionospheric plasma processes associated with the spread-F phenomenon have been the subject of active investigation by researchers since the first detailed study on spread F by Booker and Wells (1938). The discovery in mid 1970 that the spread F is associated with plasma depleted regions, or bubbles, rising through F region with a hierarchy of smaller irregularities, stimulated increasing interest as to the causes that initiate and controle the irregularity processes (Woodman and La Hoz, 1976; McClure et al., 1977; Kelley et al., 1976; Hudson and Kennel, 1975; Ossakow et al., 1979). The well-known Rayleigh-Taylor instability mechanism in its general form is believed to be basically responsible for the bubble generation having its initiation at the bottomside ledge of a rising evening F-layer (Haerendel, 1973; Anderson and Haerendel, 1979). The ambient ionospheric conditions and the perturbation sources that favour, or inhibit, the instability processes are still poorly understood. In an attempt to test the current theories on the various aspects of equatorial spread F event, an international collaborative program was conceived with participation of Brazil, USA and West Germany, to carry out active ionospheric experiments from the equatorial rocket launch base at Natal ($5^o55'S$, $35^o15'W$, -6.4 ML), Brazil. Two campaigns were planned that were complemented by an extensive array of ionospheric diagnostic instruments, including ground based and airborn, that permitted measurements extending from the vicinity of Natal eastward up to the island of Fernando de Noronha (FN) (3.83^oS; 32.5^oW, - 6.2^oML). Each rocket campaign had objective to create perturbation in the ionization, intended to initiate R-T instability process, by chemical releases at the bottomside ledge of a rising F-region. In the first of the two Campaigns, BIME, Chemical releases were carried out to create ionization holes (Narcisi, 1983). In the second Campaign called Coloured Bubbles (Haerendel et al., 1983) two big Barium vapour clouds were injected at close and equidistances from the rocket apogee, at the steep ledge of the F_2 region. Europium cloud was released at the apogee in order to track the motion of the gap between the two main Bariumclouds. Also, five small clouds were released on the upleg in order to trace the shear flow in the lower F-region (Kudeki et al., 1981; Tsunoda et al., 1981). This second campaign was a cooperative effort between the Max Planck Institute for Extra Terrestrial Physics and the Instituto de Atividades Espaciais (IAE/CTA), Brazil with support from BIME network of ground and airborne observations (Narcisi, 1983).

Two SONDA III rockets were launched, with Ba and Eu cloud release mechanism in two separate experiments, at 20:56UT on 17 September 1982 in the first one (CBI) and at 20:45UT on 18 September 1982 in the second one (CBII). The big clouds were placed at the desired heights, namely, at 322 and 320 km during the CBI and at 330 and 334 during the CBII experiments. During both the launches the F-region over Natal was stable, although it was rising up at 32 ms^{-1} and 40 ms^{-1} respectively, as indicated by the Natal Digisonde. Following the releases the big Ba clouds, getting ionized and extending along the field lines, soon drifted eastward with the background plasma motion that also had a southward component, stronger during the CBII than the CBI experiment. Optical triangulation technique, used to track the clouds till the terminator for up to 19 and 22 minutes, respectively, in the two experiments, provided precise cloud locations in height, longitude and latitude as a function of time from the instant of the release. The cloud irregularity trails that provided ionosonde returns were tracked by the Natal Digisonde and FN ionosonde. The latter was particularly useful for tracking the irregularity clouds in the dark side of the terminator for up to ~450 km eastward. VHF and UHF scintillations from the cloud induced irregularities were detected by instruments at FN and on board aircraft. This paper discusses the results from the different radio diagnostics of the cloud induced bubble irregularity growth and dynamics.

2- RADIO DIAGNOSTICS OF THE CLOUD INDUCED IRREGULARITY GROWTH AND DYNAMICS

Ionospheric response produced by the vapour release experiments were monitored by ground based as well as airborne diagnostic instruments operated at Natal and in its vicinity regions, and at Fernando de Noronha (FN) located some 310 km geomagnetically eastward of Natal. The ionosonde (a chirp sounder) and the VHF electronic polarimeter observations at FN (Abdu et al., 1983) and the airborne observations of scintillation region on FLTSATCOM propagation path (Johnson and Hocutt, 1983) were particularly useful to monitor the irregularity evolution from the eastward drifting big Ba clouds. Digisonde data from Natal (Buchau et al., 1983) were used for identifying and counter checking some of the ion cloud locations observed by the FN ionosonde. Special observations were carried out with the ionosonde at Fortaleza located some 440 km westward of Natal in order to provide control data on natural spread F irregularity generation westward of the ionospheric modification region so as to resolve possible ambiguities, such as that could result from the eastward drift of these irregularities, in the interpretation of the FN ionosonde and polarimeter data.

2.1- Cloud Induced Irregularity Signatures in the FN Ionogram and Polarimeter Data

The irregularity signatures in the FN ionograms resulting from the CBI vapour release experiment are presented in Figure 1 (inset) using range spread F index numbers (as was defined by Abdu et al., 1983) plotted as functions of the ionosonde operation frequency and local observation time starting from immediately before the launch time and covering the irregularity development phase and well beyond. Control data on natural spread F occurrence over Fortaleza are presented in the upper portion of the figure. The vertical solid lines represent the frequency limits of the satellite traces in the ionograms. It should be noted that when more than one satellite traces was present, only the more intense ones were included in this figure. Also shown in the figure are the F-layer base height (represented by h'F as well as the virtual height of the 3MHz plasma frequency) variations for FN and Fortaleza. The layer at FN was moving up, indicative of an eastward electric field, at 30 ms^{-1}, as it was over Natal, when the series of vapour releases were initiated at 17:59:30LT. The occurrence of bottomside spread F, shown here with index number 1, from 1800LT to 1805LT is unrelated to the CBI experiment. The first satellite trace detected by the FN ionosonde at 1810LT at a slant range of 405 km, higher than the F-layer base height of 350 km at this time, represented the Ba7 cloud trace approaching the ionosonde meridian from the west. In the ionogram at 1826 LT weak Ba3 cloud trace could be identified close to the Ba7 trace, both having ranges at this time slightly less than h'F. From numerous satellite traces that were present in the subsequent ionogram, those corresponding to the two clouds, getting more diffuse with time (and hence represented also by index numbers) could be identified unambiguously till 1850LT and with a certain degree of uncertainty till 1930LT. Their virtual ranges have been used to determine the eastward propagation velocities of the irregularity traces as will be discussed shortly. It is important to note that the data plot for Fortaleza shown in the upper part of the figure presents an entirely different evolution of natural spread F. (This difference lies mostly in the relatively longer persistence bottomside spread F over Fortaleza, earlier to the satellite trace onsets that usually precede the natural bubble developments. The later onset and the restricted frequency range of the satellite traces are also points of differences).

The ionospheric height changes and spread F irregularity developments over FN during the CBII experiment are presented in Figure 2. The F-layer rise velocity at the launch time was >40 ms^{-1} at FN and at Natal. Following the rocket vapour releases, the first satellite trace, presumably from Ba8, detected in the ionogram at 1754LT was at a slant virtual range of 620 km as compared to the h'F of 360 km. This trace soon developed into diffuse structures moving rapidly away from the ionosonde detection limit, which must be caused by the optically detected southward drift of the clouds under the action of rather strong southward neutral wind that was present at this time. Northward extensions of the field aligned Ba6 and Ba8 clouds were later detected in the ionogram at 1810LT, and their eastward propagations, then on, were clearly identifiable in the successive ionograms. In the course of the irregularity evolution from the Ba clouds a sporadic E layer seems to have developed at an oblique direction from FN as indicated by slant E + F trace at 1805, not specifically shown in the figure, that became diffuse and receded out of the ionosonde detection range by 1826 LT. The Ba6 and Ba8 cloud induced irregularities could be tracked by the ionosonde till 1920LT, while spread F from the ambient F-layer could be seen till 2015LT. The natural spread F over Fortaleza during the CBII, shown in the upper part of this figure, presents, as during the CBI experiment, an entirely different evolutionary characteristics compared to that over FN.

Faraday polarization rotation angle, and amplitude, of VHF satellite beacon were monitored using electronic polarimeters at FN during the CBI and CBII experiments. The total electron content (TEC) in the satellite-ground path, (represented by the Faraday rotation angle), is known to undergo significant fluctuations, in association with amplitude scintillation of the signals, during naturally occurring plasma bubble events (Abdu et al., 1985). Such fluctuations are produced by the ExB drift across the satellite line of sight of flux tube aligned transequatorial plasma depletions (and perhaps also associated enhancements) having smaller scale substructures within them. Similar TEC fluctuations were present, in association with amplitude scintillation, following both the CBI and CBII experiment, in the polarimeter data over FN (-6.2^{o} dip lat.) presented in Figure 3. The dashed thin lines,not claimed to be a unique curve, is a visual interpolation to represent the "unperturbed" TEC variation. Nevertheless, TEC decreases (or depletions), though of small magnitude, coincident with the cloud induced scintillation enhancements (onsets indicated by the vertical arrows) seem to be present in both part a and b of the Figure 3. These depletions, in fact, seem to be occurring interposed between TEC enhancements, as seen more pronounced in CBI data. Their occurrences concurrent with the scintillation enhancements do seem to point the origin of the depletions and associated irregularities to a region close to the two Barium clouds. The maximum depletions with respect to the dashed curve are $\sim 1.8 \times 10^{16}$ electrons m^{-2} and $\sim 6 \times 10^{15}$ electrons m^{-2}, representing 6 percent and 2 percent of the TEC diurnal range (Δ TEC), for the CBI and CBII experiments, respectively.

2.2- Zonal Propagation Characteristics of the Ion Clouds, and Irregularity Developments

Ionosonde observations from Fernando de Noronha have made it possible to track the eastward drifting big Ba ion clouds up to approximately 450 km into the shadow region, thus providing an important extension to the cloud positions in the sunlit side of the Terminator determined by optical triangulation technique. Since the echo azimuth and elevation information were not obtained from the FN ionosonde, the tracking of the cloud positions based on the ionogram traces involved certain assumptions on well-known features of the irregularity patch structure and dynamics. These assumptions and the ionogram interpretation method based on them are briefly explained below.

The eastward drifting big Ba ion clouds should eventually evolve into elongated field aligned trails that have irregularities developing within (and around) them. The field aligned characteristics make it necessary that the radio returns should be originating from a restricted region on the trail where field line perpendicular (or near perpendicular) reflection conditions are satisfied. (This perpendicular condition should be valid whether the ionosonde returns arise from total, or partial, reflection from density gradients, or from scattering by elongated irregularities). The reflection points for the FN ionosonde (the dip latitude of FN being -6.2^{o}) for the successive trail positions should therefore follow an isodip line (if we neglect refraction of the radio waves) somewhat southward of the ionosonde magnetic latitude. If this isodip line (or magnetic latitude) as well as the reflection point heights are known, then the precise longitudes of the reflection points as a function of local time can be determined from the Ba cloud trail slant range obtained from successive ionograms.

Theoretically the magnetic latitude of the reflection point should be about 7^{o}S, if we consider, as an example, a reflection height of 300 km in the magnetic meridional plane of FN. Experimental determination of this isodip line was possible by comparing ground projections of specific cloud positions simultaneously determined from FN ionograms and from Natal digisonde data. Thus, in Figure 4 the Ba7 ground ranges observed from FN at 1810LT, 1826LT, 1830LT and 1840LT were made to intersect with the Ba7 ground ranges observed at the same (or close by) local times by the Natal digisonde (Buchau et al., 1983). Appropriate group retardation factors were applied to the FN ionogram virtual ranges in order to obtain the ground ranges marked in Figure 4. The mean magnetic latitude for these intersection points came out to be very close to -7.1^{o}, in good agreement with the estimate given above. All the cloud reflection point longitude determinations in our analysis were thus based on the justifiable assumption that the ionosonde returns over FN originated at, or very close to, this reference latitude and that the field aligned Ba cloud irregularity patches were drifting eastward. It should be pointed out, however, that small departures from this reference latitude will not introduce any significant alterations in our final results.

The variations in Ba cloud heights during their eastward drifts do not necessarily follow that of the ambient ionosphere due to the polarization electric fields set up in the clouds. During both the CBI and CBII experiments the optical measurements have detected downward velocities for the cloud centers. The electric field could cause the cloud center velocity component in the magnetic meridional plane, v_m, to make an angle δ(where $\delta = \tan^{-1}(v_z/v_s) - I$, v_z and v_s representing the downward and southward velocity components of the cloud centers, and I being the dip angle) with respect to the field line such that the vertical velocity, v_{zr}, of the reflection point should actually be given by $v_{zr} = v_m \mathrm{Sin}\delta/\mathrm{Cos}I$. The sense of v_{zr}, whether downward or upward, and its magnitude would depend upon the direction and magnitude of the cloud polarization field relative to the ambient electric field. For the sunlit part of the terminator, the v_{zr} values could be deduced from optical data. Their values in the shadow region, necessary to determine the Ba trail reflection point heights, were deduced on the assumption that the Ba trace range in the ionogram presented a minimum when the cloud irregularity trail crossed the magnetic meridian of the ionosonde location. The v_{zr} value thus deduced (and assumed to be constant throughout the observation duration) was used to obtain the Ba trail heights in the successive ionograms which were then inputs, together with their slant ranges, in the determination of the reflection point longitudes.

The geographic longitudes of the cloud irregularity positions calculated using the above procedure were then projected along magnetic meridional directions on to a reference geographic latitude that was arbitrarily taken as that of the last optically determined ion cloud center location (see Figure 4). We shall denote the resulting new cloud longitude simply as geomagnetically projected longitude of the ion clouds irregularities. All the preceding optically located Ba cloud longitudes were also projected on to the same reference latitude. This procedure is found to be useful for the Brazilian equatorial region (where the magnetic declination angle, 22^{o}W, is a global maximum) to achieve a better perception of the zonal velocity of the magnetically eastward drifting Ba cloud irregularities.

Figure 5 presents a local time versus longitude plot of the CBI Ba3, Ba7 and Eu cloud center locations optically determined till about 1818LT, and the continuing drift further eastward of the two Ba cloud irregularity patches as tracked by the FN ionosonde. The retardation factor that resulted from this calculation was 8 km (in the equivalent vertical direction) and the v_{zr} values were 15 ms^{-1} and 13 ms^{-1}, respectively, for the Ba3 and Ba7 clouds. Also plotted in this figure are the Ba7 locations at 1811, 1821, 1826 and 1841LT determined by the Natal digisonde (Buchau et al., 1983). They agree very well with the Ba7 trace locations determined from the FN ionograms.

Amplitude scintillation occurrence on SIRIO VHF beacon registered by the FN polarimeter (Figure 3) are also marked in Figure 5. The longitude of the irregularities (namely, the geomagnetically projected longitude) corresponds to the cloud irregularity patch height at the onset of the 1854LT scintillation enhancement that was ~310 km. This scintillation enhancement (shown by the enhanced width of the shaded area) clearly coincides with the passage of the Ba clouds trails. It is not clear, however, if the earlier 1846LT weak scintillation onset is in any way related to the Ba clouds. If it is a natural event (which most likely it is) its longitude should be located further eastward (though not shown as such in the figure) appropriate for the F-layer subionospheric height that at this time was ~400 km. The longitude boundaries, westward and eastward, of the scintillation producing irregularities measured on Aircraft-FLTSATCOM path (Johnson and Hocutt, 1983) are marked by W and E respectively. It turns out that in the initial stage the scintillation region tracked by the aircraft corresponds to the cloud location identified in the ionogram as that of the Ba3, and later on it merges with the Ba7 location. An important feature to be noted in Figure 5 is that there is an increase in the eastward irregularity patch velocity from ~55 ms^{-1} before 1845LT to the order of 140 ms^{-1} soon afterwards (the velocities in the magnetic east direction will be 0.9 times these values). A tendency for a similar velocity change is also seen in the eastern edge of the scintillation region in the aircraft data of Johnson and Hocutt (1983). The tendency for a decrease in the velocities seen after 1910LT from the FN ionosonde data should not be treated seriously since some uncertainty has been present in the precise slant range determination of the increasingly diffuse Ba3 and Ba7 traces in the ionograms at these times. The range spread F occurrence in the FN ionogram (arising mainly from the Ba3 and Ba7 cloud traces) marked by index numbers 1, 2, etc. at the geomagnetically projected longitude of FN seems to agree perfectly with the passage over FN of the enhanced scintillation region detected by the polarimeter.

Results from Coloured Bubble II experiment are presented in Figure 6. The v_{Zr} values that resulted from these calculations were 15 ms^{-1} and 12 ms^{-1} for the big clouds, Ba6 and Ba8 respectively, and the retardation factor was 10 km. The optically tracked Ba6, Eu and Ba8 cloud positions are plotted till 1810LT and from then on the eastward propagating cloud irregularity patches clearly identifiable in the FN ionogram are plotted till 1920LT in Figure 6. Scintillation events on SIRIO-FN path that had onsets at 1816LT and 1854LT as seen in Figure 3 are also plotted in Figure 6. The latter of these events, plotted at a geomagnetically projected longitude, corresponding to the irregularity height of 300 km,does seem to be clearly associated with Ba cloud induced irregularities. Also plotted are the range spread index numbers 1, 2, etc., mostly produced by the ion cloud irregularity patch. The weak scintillation onset at 1816LT followed by an enhancement at 1821LT does not seem to be produced by irregularities in the immediate vicinity of the ion clouds. It seems to have developed eastward of FN and drifted away further eastward. In fact, the FN ionograms showed the development of a spread F patch, from an oblique trace at 1815LT, and its decay or drifting away by about 1830LT (not shown in Figure 2) which might perhaps be identified with this earlier scintillation event. Its possible association with the CBII cloud release is not clear. The west and east boundaries of the VHF scintillation region monitored by Johnson and Hocutt (1983) on aircraft-FLTSATCOM propagation path are marked by W and E,respectively, in Figure 6. They seem to agree well with the irregularity patch positions associated with Ba6 as identified by the FN ionosonde.

It is important to note that the local time versus longitude curve presents a marked increase in the eastward velocity to 150 ms^{-1} after 1830LT from approximately 60 ms^{-1} before, which is very similar to the feature, also near the same local time, observed in the CBI data plot of Figure 5. Similar increase in the eastward velocity is seen also in the western boundary of the irregularity patch observed from Aircraft by Johnson and Hocutt (1983). Another important observation from Figure 6 is perhaps the fact that the scintillation onset on SIRIO path at 1854 represents irregularity occurrence on the rear side of Ba8 also very similar to the observation during the CBI experiment. The ionogram "spread F" occurrence onset with weak intensity (index 1) at 1840LT is in agreement with this conclusion from the polarimeter data.

3- DISCUSSION AND CONCLUSIONS

Combined optical and radio measurements during the Coloured Bubble I and II experiments have made it possible to investigate the Ba ion cloud eastward drift and irregularity evolutions, starting from the Ba cloud release points in the sunlit side of the Terminator to some 500 km eastward, into the shadow region. The zonal drift velocities of the clouds and their time variations, reflecting the rapidly changing electrodynamic conditions of the evening equatorial ionosphere, could be monitored by the coordinated measurements more successfuly during the CBII experiment than during the CBI experiment. (Difficulty in determining unambiguous FN ionogram cloud trace ranges at later phase of the irregularity development seems to have affected a clear assessment of the cloud irregularity motion at these times in the CBI data). The most crucial question to be answered from these results has to do with that of the ionospheric bubble irregularity generation initiated by the big Ba vapour clouds. The results presented above from FN ionosonde and Polarimeter and from the aircraft-FLTSATCOM scintillation observations and, in a complementary way, from the Natal Digisonde do provide positive evidences that bubble irregularity generation was indeed initiated by the vapour cloud releases.

The FN ionosonde did detect irregularity development at the bottomside edges (the regions sensitive to ionosonde technique) of the eastward drifting Ba clouds both during the CBI and CBII experiments. The irregularity development sequence, starting from clear Ba ion cloud traces, as registered by the FN ionogram, has certain resemblance to that of the natural spread F plasma bubble events that often evolve out of clear satellite traces in the ionograms. The spread F indices, however, might suggest, qualitatively at least, that the intensity of the vapour cloud induced irregularity event was not typical of a very intense one.

The FN polarimeter data have detected the presence of amplitude scintillation of moderate intensity coincident in time with relative TEC depletions. These depletions were of the order of 6 percent of the ΔTEC during the CBI and 2 percent during the CBII, which are significant in comparison with the depletions often observed in naturally occurring plasma bubble substructures (Abdu et al., 1985). Substructures having magnitude of 1-5 percent of ΔTEC and field line perpendicular scale sizes on the order of 60-70 km, superposed on large scale depletion events of upto 30 percent magnitude and of up to ~400 km scale sizes, have often been observed from polarimeter experiments in Brazil (Abdu et al., 1985). The rather close proximity between such substructure scale sizes and the big Ba cloud release point spacings used in the CBI and CBII experiments (namely, 71 km and 59 km, or 67 km and 55 km, perpendicular to field lines) is merely a fortuitous coincidence. It is interesting to note that the scale sizes suggested by the TEC oscillations, centered around the local times of the scintillation onsets (indicated by arrows), both in the CBI and CBII data, are in fact comparable, considering the vapour cloud eastward velocities observed at these time, with the original big Ba cloud release point spacings. This point might signify that the TEC depletions were interposed by relative enhancements in TEC. Theoretically the degree of the depletion in a bubble should depend upon the amplitude of the initial perturbation acting as the trigger source, besides such factors as the field line integrated ambient electron density gradient scale length and the ion neutral collision frequency (Haerendel, 1973; Anderson and Haerendel, 1979; Ossakow et al., 1979). Precise polarimeter determination of depletions magnitude would,however, depend very much on the alignment of the bubble depletion axis with the satellite line of reception. Possible variabilities in the degree of this alignment, that could be caused by variabilities in the E and F-region wind and conductivity profiles, could explain at least in part the difference between the TEC depletion amplitudes observed in the two CB experiments (Figure 3).

The VHF scintillation boundary and its eastward drift, as observed on the Aircraft-FLTSATCOM path (Jonhnson and Hocutt, 1983) and plotted in Figures 5 and 6, agree in general with the eastward drift of the ion cloud irregularities as tracked by the FN ionosonde. The CBII results of Figure 6, that provide statistically better reliable velocities show, further, that during the initial 40-45 minutes the eastward velocity of the scintillation region western boundary is perceivably less than that of the ionosonde cloud trace. Assuming that this initial period does cover a major part of the cloud induced bubble growth phase,we can arrive at an estimate of the rise velocity of the bubble, as follows. The eastward velocity from the aircraft data centered around 18:25LT comes out to be 43 ms^{-1}, whereas the corresponding velocity from the ionosonde cloud trace comes out to be 62 ms^{-1}. Since the satellite look angle from the aircraft was eastward ($\sim 18^{0}$),the western boundary of the scintillation region observed by the aircraft should, in fact, represent a projection, in the horizontal plane, of the bubble vertical growth. Assuming, further, that the growth is vertically upward (which is not necessarily valid always),the data in Figure 6 would yield a rise velocity of ~ 57 ms^{-1}, centered around 18:25LT, which seems to be reasonable on the bases of radar and satellite results on naturally occurring plasma bubbles (McClure et al., 1977; Tsunoda, 1981). If we take into consideration possible westward tilt of the bubble axis during the growth phase as has frequently been observed by radars (Woodman and LaHoz, 1970; Tsunoda, 1981), and as could be expected from the wind and conductivity height structures at these times, the 57 ms^{-1} obtained above would in fact represent an upper limit for the rise velocity of the cloud induced bubble growth during the CBII experiment.

It looks clear now that the ambient F-region,though stable, was indeed propicious for bubble irregularity developments from perturbations initiated by the big ions clouds. The maximum scale sizes seem to be determined by the original cloud spacing, whereas the depletion magnitude (not completely known from our measurements) might be dependent, among other factors, on the initial cloud induced perturbations amplitude as well. Although the determination of depletion magnitudes from our measurements was subject to limitations dictated by the observing geometry,their good similarity with the naturally occurring plasma depletions substructures observed in other measurements using identical observing geometry would suggest that the cloud induced initial perturbation amplitudes must have been adequate to initiate bubble developments of significant amplitude. A detailed numerical modeling of the bubble generation from well-known plasma instability processes,using realistic ambient ionospheric condiitons and CBI and CBII input data, could lead to a more quantitative evaluation of these results. In any case the positive evidences presented above do testify to the success of CB experiments in triggering plasma bubble irregularity generation from Ba cloud perturbations introduced at the stable bottomside electron density gradient region of a rising equatorial F-region.

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FIGURE CAPTIONS

Figure 1 - F-layer heights (h'F - dashed line, and the virtual height of 3 MHz plasma frequency-solid line) and range spread F development over Fernando de Noronha and over Fortaleza during the Coloured Bubble I experiment on 17 September 1982. The SONDA III rocket launch time at 1756 LT is indicated. In the inset figure the index numbers 1, 2, 3, etc. are used to represent the range spread development as a function of ionosonde frequency and local time. The vertical solid lines represent limits of satellite trace in the ionogram. Such details as their proximity to the main F-layer trace and their range separations are not shown in this figure. Also, when several satellite traces are simultaneously present in an ionogram only the more intense ones are marked in the figure.

Figure 2 - The F-layer height and range spread F development during the Coloured Bubble II experiment presented in the same format as in Figure 1.

Figure 3 - Tracings of the polarimeter phase, ϕ, ($\propto$ TEC), the upper curve, and amplitude, the lower curve, on SIRIO VHF beacon received at Fernando de Noronha during the Coloured Bubble I experiment in the upper frame (a) and during the Coloured Bubble II experiment in the lower frame (b). In the ϕ curve a change of 10^0 represent a change of approximately 2×10^{16} electrons m^{-2} in the SIRIO-FN propagation path, namely 1.88×10^{16} electrons m^{-2} in the equivalent vertical column. Amplitude calibration in dB is also shown in the figure.

Figure 4 - Latitude versus longitude plots of Ba3 and Ba7 (CBI) ground projections at successive local times, as determined from optical triangulation method plotted as open and filled triangles respectively. The Ba7 ground projections determined from successive FN ionograms, as explained in the text, are marked as solid circles. The horizontal range of the Ba7 cloud position from FN at 1810LT, 1826LT, 1830LT and 1840LT are made to intersect with their horizontal ranges at the same, or close by times, from Natal as measured by Buchau et al. (1983). The magnetic dip latitude and the meridional directions are shown in background. The reference geographic latitude namely, that of the last optically tracked Ba7 cloud is shown at 5.6^{o}S. (The last three solid triangles are the extrapolated Ba7 locations and hence they could fall out of the reference latitude). All the Ba7 ionosonde trace ground projections, the SIRIO subionospheric point and FN have also been projected on to this reference latitude for preparing Figures 5 and 6.

Figure 5 - Longitude versus local time plots for Ba3, Eu and Ba7 cloud locations optically tracked till 1818LT and the Ba3 and Ba7 cloud irregularity position determined from FN ionograms (as explained in the text) from 1820LT till 1930LT. W and E represent the west and east boundaries, respectively, of the UHF scintillation region ground projections obtained from Aircraft-FLTSATCOM path by Johnson and Hocutt (1983). (The W at 1854LT represents the western boundary of an irregularity enhancement, while the further westward extending weaker irregularity region has the boundary marked by W at 1846LT). VHF scintillation on FN-SIRIO path is indicated by the shaded patch begining at 1846LT and range spread F intensity over FN is marked by index number 1, 2, etc. starting from 1845LT. FN is marked on geomagnetically projected longitude (see Figure 4). The short vertical lines adjacent to the Ba3 and Ba7 cloud positions are the geomagnetic projections as explained in the text.

Figure 6 - Longitude versus local time plots of Ba6, Eu and Ba8 clouds as in Figure 5. The Ba6 and Ba8 irregularity locations were deduced from FN ionogram data from 1820LT till 1920LT. All explanations are the same as for Figure 5. The point W near 1842 in fact represents the western boundary of an irregularity enhancement region while the much weaker irregularity region that extends further westward has the boundary marked by W at 1836LT).

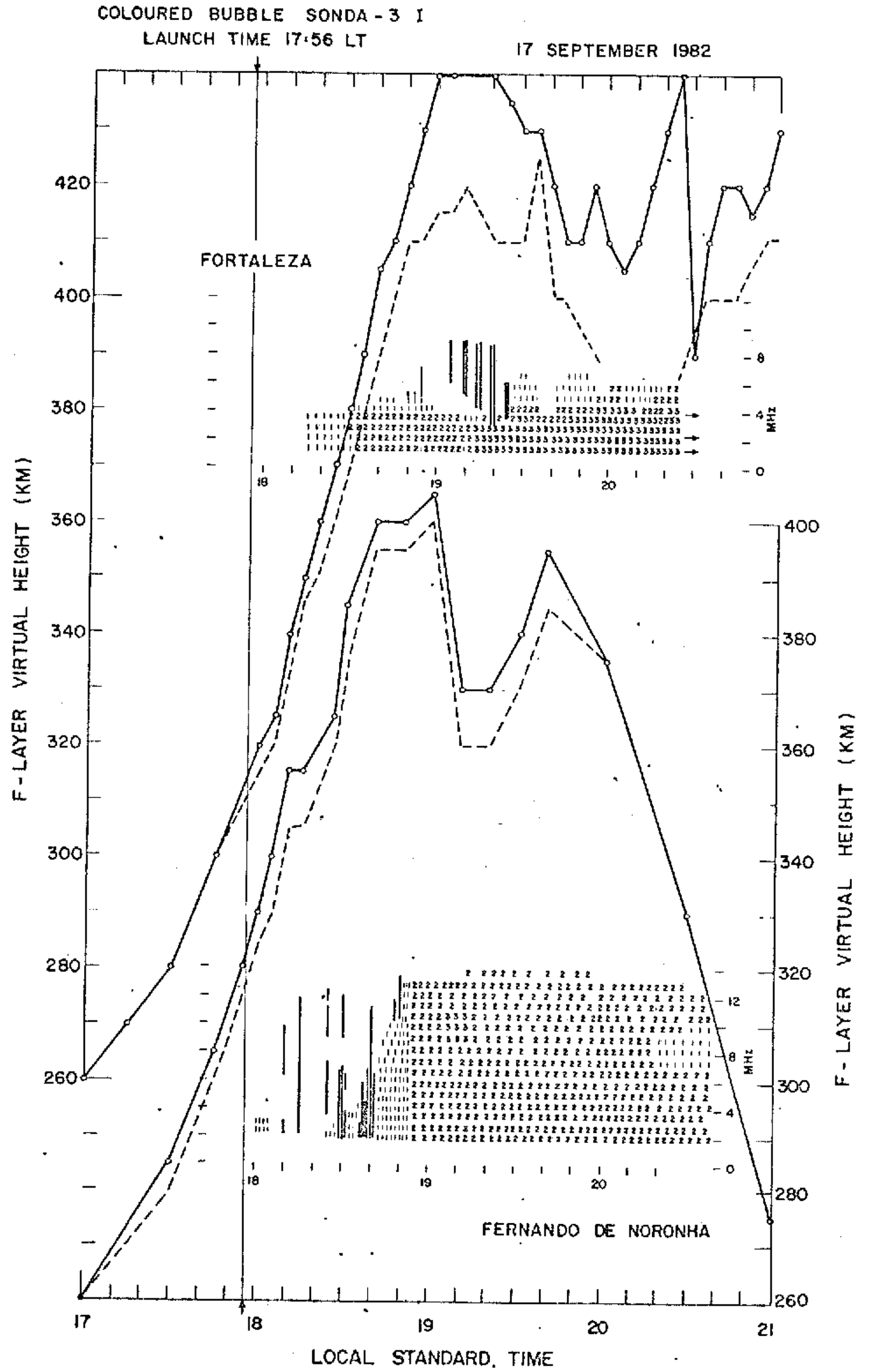
COLOURED BUBBLE SONDA - 3 I
LAUNCH TIME 17:56 LT
17 SEPTEMBER 1982
FORTALEZA
FERNANDO DE NORONHA
F - LAYER VIRTUAL HEIGHT (KM)
LOCAL STANDARD TIME
MHz
17
18
19
20
21
260
280
300
320
340
360
380
400
420

Fig. 1

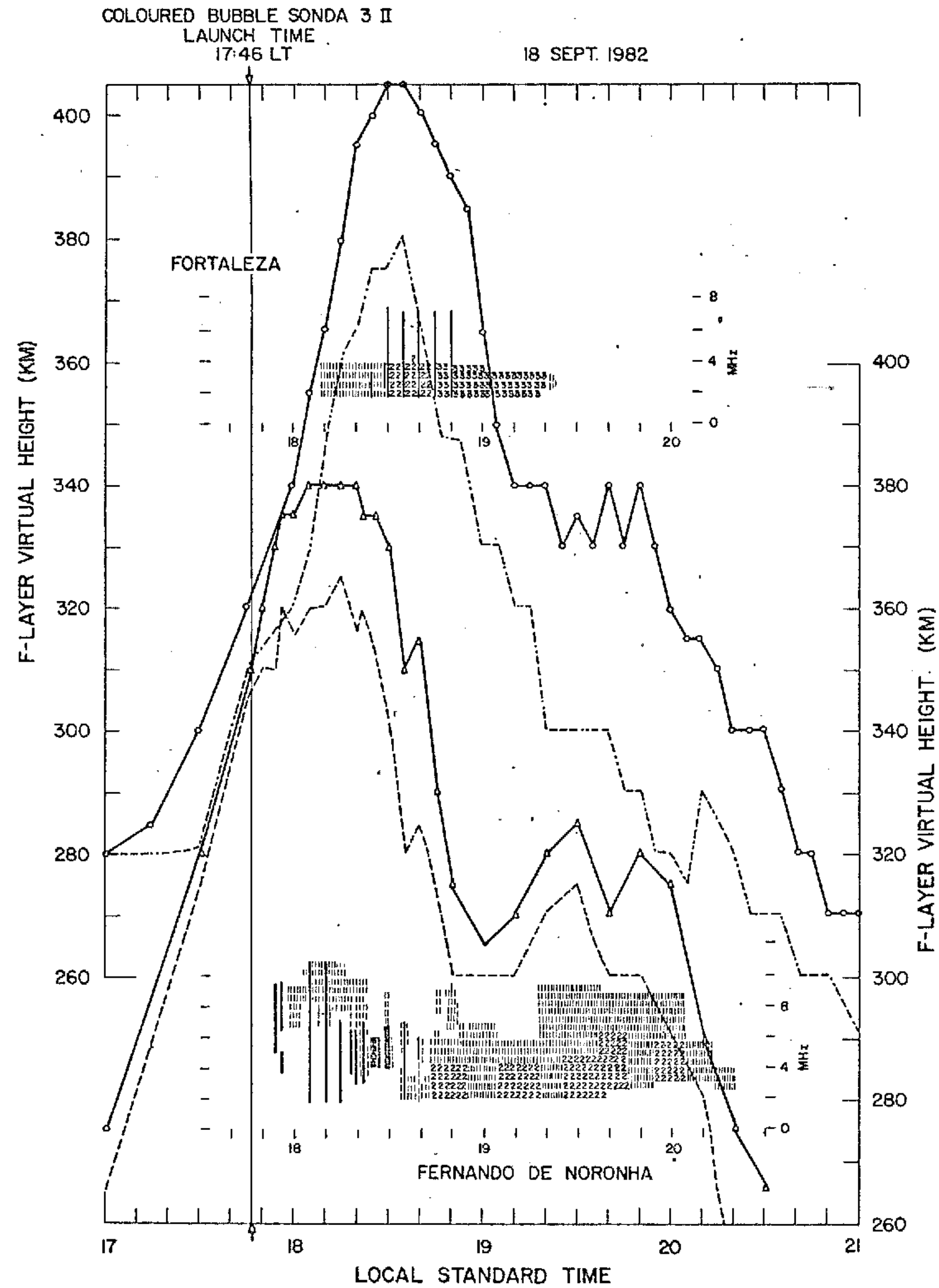
COLOURED BUBBLE SONDA 3 II
LAUNCH TIME
17:46 LT
18 SEPT. 1982
FORTALEZA
FERNANDO DE NORONHA
F-LAYER VIRTUAL HEIGHT (KM)
LOCAL STANDARD TIME
MHz

Fig. 2

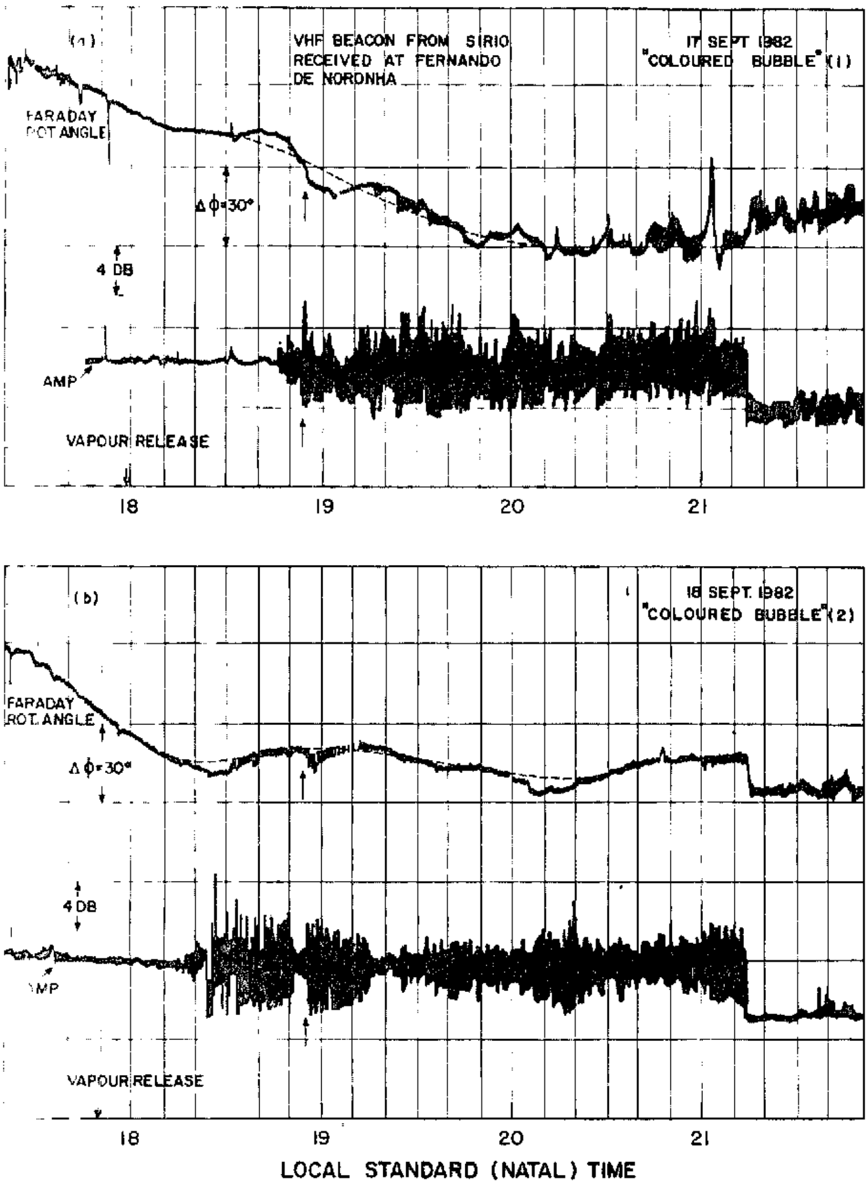
(a)
VHF BEACON FROM SIRIO
RECEIVED AT FERNANDO
DE NORONHA
17 SEPT 1982
"COLOURED BUBBLE" (1)
FARADAY
ROT ANGLE
Δφ=30°
4 DB
AMP
VAPOUR RELEASE
18
19
20
21
(b)
18 SEPT. 1982
"COLOURED BUBBLE" (2)
FARADAY
ROT. ANGLE
Δφ=30°
4 DB
AMP
VAPOUR RELEASE
18
19
20
21
LOCAL STANDARD (NATAL) TIME

Fig. 3

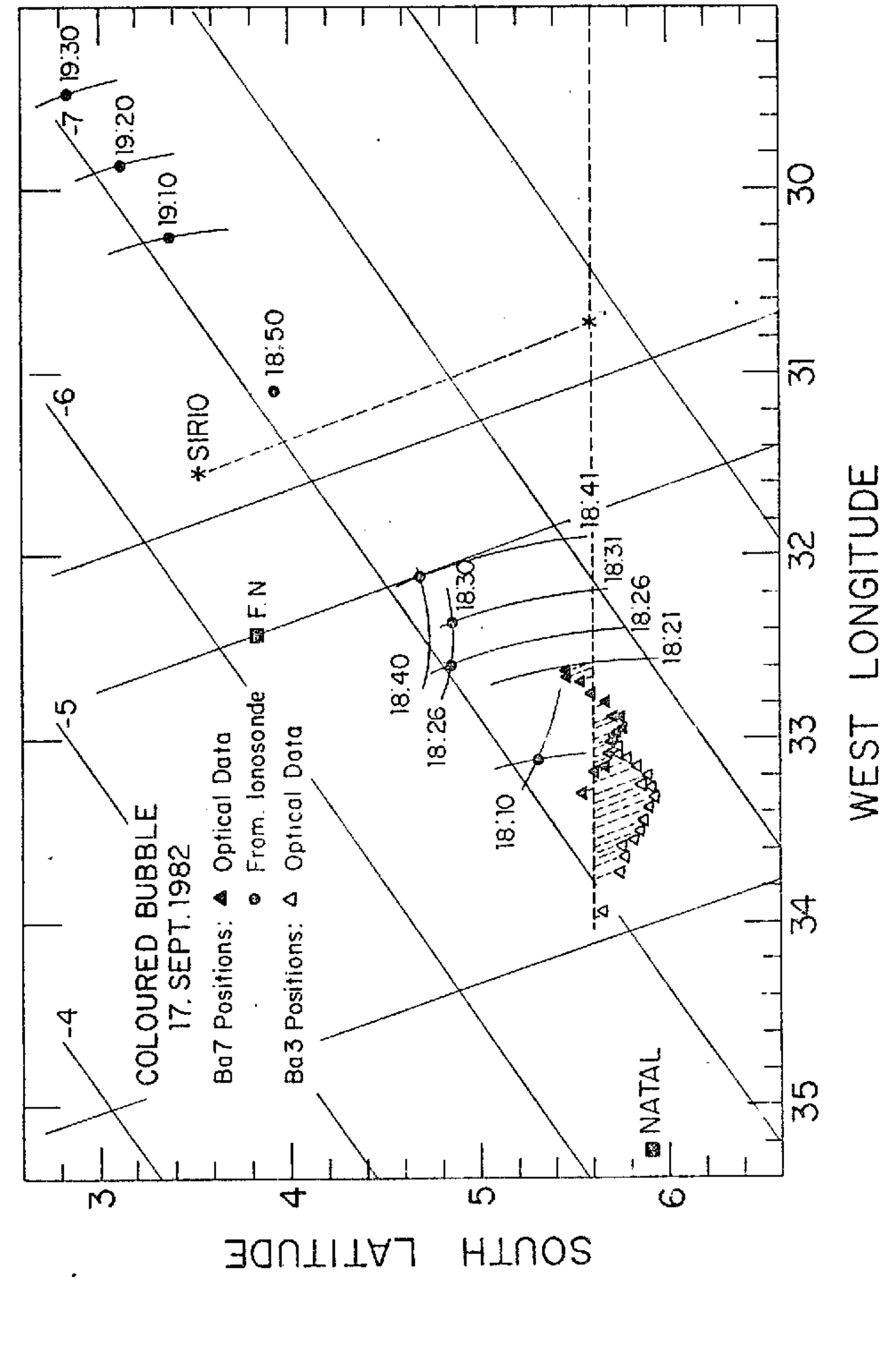
COLOURED BUBBLE
17. SEPT. 1982
Ba7 Positions: ▲ Optical Data
○ From. Ionosonde
Ba3 Positions: △ Optical Data
SIRIO
F.N
NATAL
19:30
19:20
19:10
18:50
18:41
18:31
18:26
18:21
18:40
18:30
18:26
18:10
-4
-5
-6
-7
3
4
5
6
30
31
32
33
34
35
SOUTH LATITUDE
WEST LONGITUDE

Fig. 4

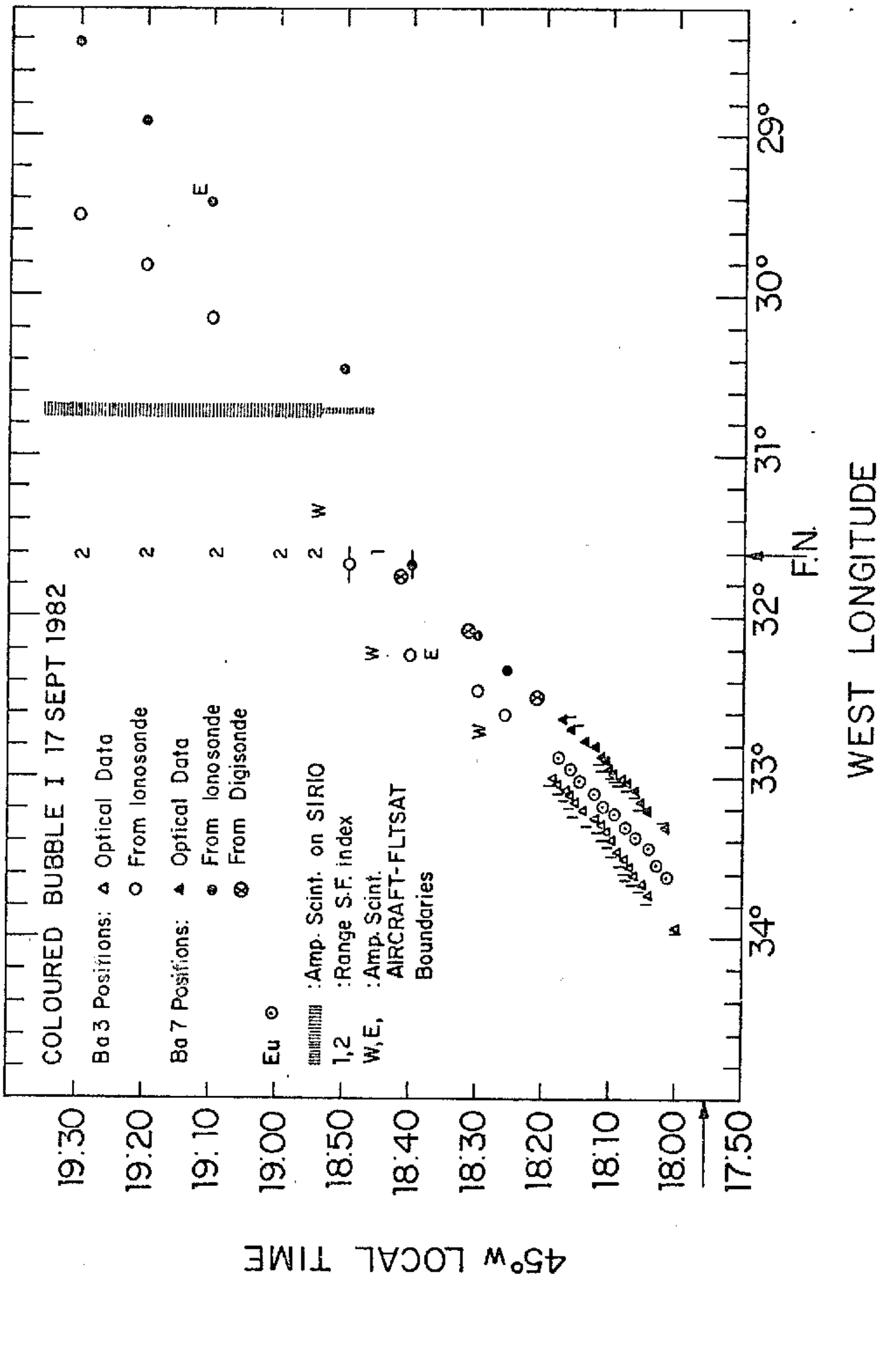
COLOURED BUBBLE I 17 SEPT 1982
Ba 3 Positions: Optical Data
From Ionosonde
Ba 7 Positions: Optical Data
From Ionosonde
From Digisonde
Eu
:Amp. Scint. on SIRIO
1,2 :Range S.F. index
W,E, :Amp. Scint. AIRCRAFT-FLTSAT Boundaries
45°w LOCAL TIME
19:30
19:20
19:10
19:00
18:50
18:40
18:30
18:20
18:10
18:00
17:50
34°
33°
32°
31°
30°
29°
F.N.
WEST LONGITUDE

Fig. 5

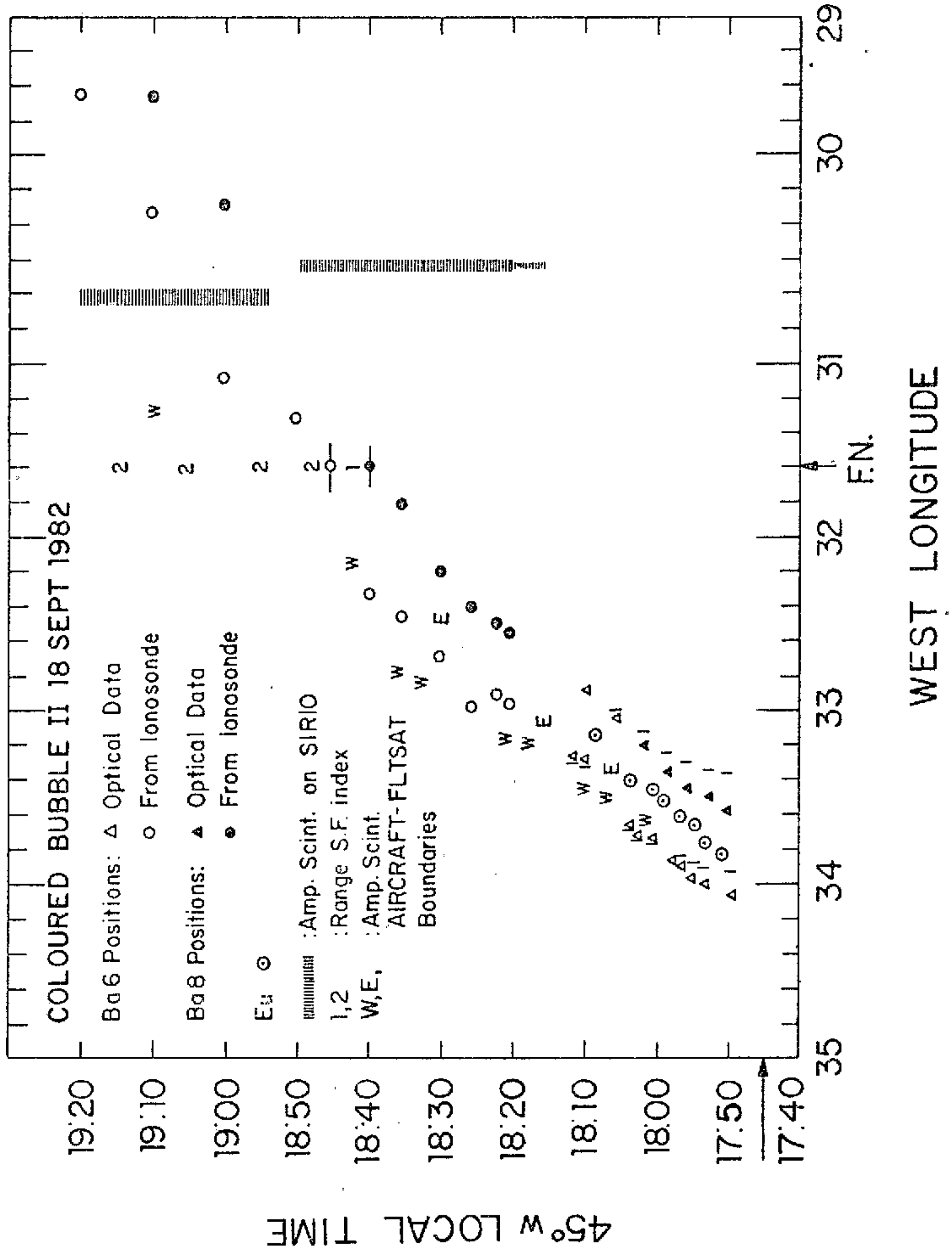
COLOURED BUBBLE II 18 SEPT 1982
Ba 6 Positions: △ Optical Data
○ From Ionosonde
Ba 8 Positions: ▲ Optical Data
● From Ionosonde
E: ⊙
:Amp. Scint. on SIRIO
1,2 :Range S.F. index
W,E, :Amp. Scint.
AIRCRAFT-FLTSAT
Boundaries
45°W LOCAL TIME
19:20
19:10
19:00
18:50
18:40
18:30
18:20
18:10
18:00
17:50
17:40
35
34
33
32
31
30
29
F.N.
WEST LONGITUDE

Fig. 6