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NASW-4045

MODELING AND INVESTIGATIVE STUDIES OF JOVIAN LOW FREQUENCY EMISSIONS

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SwRI Project 15-8558

Final Report

August 31, 1986

to

National Aeronautics and Space Administration
Washington, DC 20546

Attention: Dr. Jergen Rahe
Planetary Astronomy Program

Principal Investigator:

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EXECUTIVE SUMMARY

Jovian decametric (DAM) and hectometric (HOM) emissions were first observed over the entire spectrum by the Voyager 1 and 2 flybys of the planet (Warwick et al., 1979). The emissions are intriguing in that they display unusual "arc-like" structures on frequency-versus-time spectrograms. The source mechanism(s) of these emissions are not completely known, nor are the propagation properties. The Io torus which completely surrounds Jupiter can act as a curtain and source of refraction as well as a possible source of emission for the lower frequency emissions. Io itself is believed to be the source of Alfvén waves which precipitate particles along the Io flux tube to generate the DAM and, perhaps, the HOM emissions. One of the best ways to investigate the propagation properties of such plasma waves in a complex inhomogeneous magnetosphere is through ray tracing. Such studies can ultimately provide necessary information for the solution of the wave generation mechanism.

In this project, NASW-4045, development of software for the modelling of the Jovian plasma and magnetic field environment has been performed. In addition, an extensive library of programs has been developed for the retrieval of Voyager Planetary Radio Astronomy (PRA) data in both the high and low frequency bands from new noise-free, re-calibrated data tapes. This software allows the option of retrieving data sorted with respect to particular sub-Io longitudes. This has proven to be invaluable in the analyses of the data. Graphics routines have also been developed to display the data on color spectrograms.

We have completed a publication entitled "Ray Tracing of Jovian Decametric Radiation From Southern and Northern Hemisphere Sources: Comparison With Voyager Observations". This will be published in the Journal of Geophysical Research. This paper indicates that the current understanding of non-Io emissions may be in error, in that sources in the southern hemisphere of Jupiter along Io flux tubes can produce "non-Io" emission. In addition, a paper entitled "Jupiter's Decametric Source Locations" will be presented at the Second Annual Neil Brice Memorial Symposium on the Magnetospheres of the Outer Planets (SANBMSMOP). The influence of sources located in the Jovian auroral zone is discussed in this study. We are currently ray tracing HOM emission from source regions along the Io flux tube and comparing these model results to the PRA observations. The Io torus has been noted to strongly influence the ray path of the HOM emissions. This work will be submitted to the Journal of Geophysical Research. We are also conducting on-going production of sorted (with respect to sub-Io longitude) PRA data plot files for future investigations.

All of these efforts have resulted in a comprehensive set of software investigative "tools" which can be applied to the Voyager PRA data for future analyses. We have accomplished all of the tasks outlined in the work statement of the project. The research completed and presently being conducted will be of interest to the scientific community.

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INTRODUCTION

The complete spectrum of Jovian decametric (DAM) and hectometric radiation (HOM) was first observed by the Voyager Planetary Radio Astronomy (PRA) experiment (Warwick et al., 1979). One of the most striking features of the Jovian DAM emissions in frequency-time spectrograms, are "arc-like" bands (cf. Boischot et al., 1981). The frequency range of the arc emissions is from 1 to almost 40 MHz, but not all arcs span this complete frequency range. Several different types of arcs have been recognized in the data, depending on their curvatures which either open toward increasing time (vertex early) or open toward decreasing time (vertex late). In general, an arc may appear either as an isolated feature or there may be a series of nested arcs. In addition, the occurrence of many, but not all DAM arcs is related to the position of the satellite Io (cf. Alexander et al. 1981). The hectometric emissions have displayed similar arc structures but have been much less studied. It has been suggested (Carr et al., 1983) that HOM emissions are the low-frequency extension of DAM emissions and do not require a unique source mechanism. Detailed descriptions of the Jovian decametric arcs and hectometric emissions can be found elsewhere (ie., Warwick et al., 1979; Leblanc, 1981; Boischot and Aubier, 1981; Carr et al., 1983).

A general feature of most propagation theories of the DAM arc-producing mechanism is that the emission occurs along conical sheets that are swept past the observer as the planet rotates as first suggested by Dulk (1967). Many investigators attribute the emission to precipitating electrons along the Io magnetic flux tube which radiate near the gyrofrequency (Goldreich and Lynden-Bell (1969); Smith (1976); Goldstein and Goertz, 1983). Goldstein and Thieman (1981); Pearce (1981); Staelin (1981); Neubauer, (1980) have shown that arc-like structures are produced by a conical sheet model although no simple choice of parameters has been found which reproduces the data in detail. As shown by Goldstein and Thieman (1981) and Menietti et al. (1984), the arc curvature which varies on a frequency-time spectrogram from almost zero to quite dramatic loops (great arcs) may result from variations of the wave normal angle as a function of frequency in the source region.

One of the intriguing observations of both Voyager 1 and 2 is the often apparent independence of HOM and DAM emissions. While good association often exists between DAM and HOM emissions, there are many instances when the HOM and DAM emissions appear to have different sources, because the curvature of the DAM arcs is opposite to that of the HOM arcs.

One of the best ways to comprehensively investigate the emission and propagation of plasma waves in an inhomogeneous medium such as the magnetosphere of Jupiter is through ray tracing. Such studies require an accurate model of the plasma and magnetic fields. In this project we have utilized the most recent published results of Jovian plasma models (Divine and Garrett, 1983) and Jovian magnetic field models (Smith et al., 1976) to perform ray tracing of both DAM and HOM emissions from low-altitude sources on Jupiter.

The project, "Modelling and Investigative studies of Low Frequency Emissions in the Jovian Magnetosphere", NASW-4045, was to have been a three year program of protracted studies of decametric (DAM), hectometric (HOM) and kilometric (KOM) emissions in the Jovian magnetosphere. The first year of the

program was to have been primarily devoted to software development for the retrieval and display of Voyager planetary Radio Astronomy (PRA) data. As a result of the cancellation by NASA Headquarters of data analysis funding for all but the first year of the project, the goals were modified to complete the software development and attempt some limited ray tracing studies. As defined in the work statement of the new reduced project, development of software for the sorting and display of re-formatted, noise-free Voyager 1 and Voyager 2 Planetary Radio Astronomy instrument data was to be performed. In addition, if time allowed, ray tracing of DAM and HOM from sources located at the foot of the Io flux tube was to be conducted. We are pleased to state that each of the above tasks was performed, and research is continuing to the present time.

In this report we present some of the results of software development and graphic display accomplished to date (Part I) and the completed and on-going research investigations (Part II as well as the appendices). In Appendix 1 we include a paper, completed under the project, which will be published in the Journal of Geophysical Research with minor corrections requested by one of two referees. This paper will also be presented at the Second Annual Neil Brice Memorial Symposium on the Magnetospheres of the Outer Planets (SANBMSMOP). Appendix 2 contains an abstract to a second paper which will also be presented at the above symposium and will also be submitted to the Journal of Geophysical Research for publication. This study involves the ray tracing of sources from the foot of magnetic field lines which are anchored within the Jovian auroral zone. A third study is currently underway which involves ray tracing hectometric emissions from sources located at the foot of the Io flux tube.

I. SOFTWARE DEVELOPMENT

The ray tracing code is based on the Stix cold plasma formulation and solves the Haselgrove (1956) equations for the index of refraction. Since the index of refraction is dependent both on plasma density and on the magnetic field, an accurate model of each is necessary in order for proper definition of ray path trajectories. At the beginning of the project, the code resided on a Cyber 170. We have transferred the code to a VAX 11/750 and converted it to the modern FORTRAN 77 language. In the present code, we have incorporated the plasma model published by Divine and Garrett (1983), and the Jovian ionospheric model published by Hashimoto and Goldstein (1983). This effort involved coding not only the expressions for the density of the particle species, as published by Divine and Garrett, but also derivatives of these expressions with respect to r , θ , and ϕ . The model was tested and contours of the plasma density for a number of ion species are included as Figures 1, 2, and 3.

The magnetic field models chosen for incorporation into the code included the GSFC O-4 model (Acuna and Ness, 1979), and the P10+P11 (3,0) model (Smith et al., 1976). As discussed in the publication of Appendix 1, it appears that the P10+P11 model produced results which best agreed with the ray tracing results.

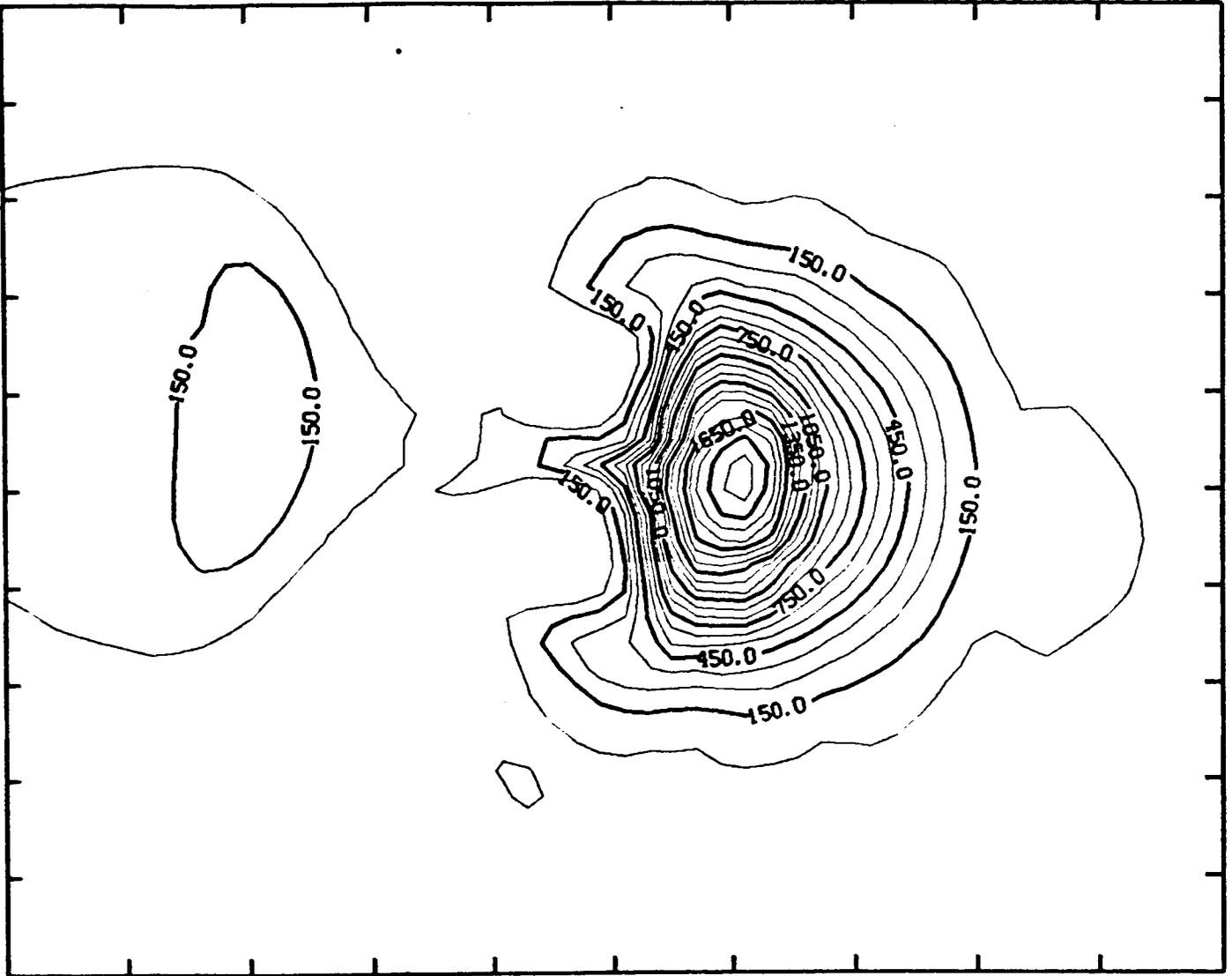
The output of the code is a list of positions of a ray at a specific frequency. The code has been modified such that at preset distances of the ray from the planet, output is sent to a file containing plottable information. These results can be directly compared to actual data plots in an effort to better understand the propagation and possible source location of various wave modes. We have developed plot programs which superimpose the ray positions as determined by the ray tracing code onto the spectrograms of the actual data.

The original data tapes supplied to our team by Goddard Space Flight Center contain information that is unfiltered in terms of noise and also contain a miscalibration in the high band data near the antenna resonance frequencies (9 to 12 MHz). For these reasons we have obtained new reformatted Voyager data tapes from Professor Thomas Carr of The University of Florida. These tapes have been filtered to remove much of the noise and also contain correctly calibrated data in the antenna resonance band.

Much effort has been applied to writing software which reads these new tapes. This task was deemed quite important because contamination of the data by interference and noise is very hard to remove and definitely has interfered with our efforts to interpret features on the spectrograms. The result of our efforts has been the development of a complete directory of programs for the retrieval and display of specific files of Voyager PRA data. This data can be requested by spacecraft day number or the data can be sorted and retrieved according to the sub-Io longitude. This has been done both for the high band (3 MHz to 40 MHz) and the low band (1 kHz to 3 MHz) frequencies.

In addition, we have developed color graphics software for frequency versus time (spacecraft longitude) spectrogram display. Spectrograms of Voyager data that have been sorted such that the sub-Io longitude is constant have been particularly valuable at displaying features that are Io-dependent.

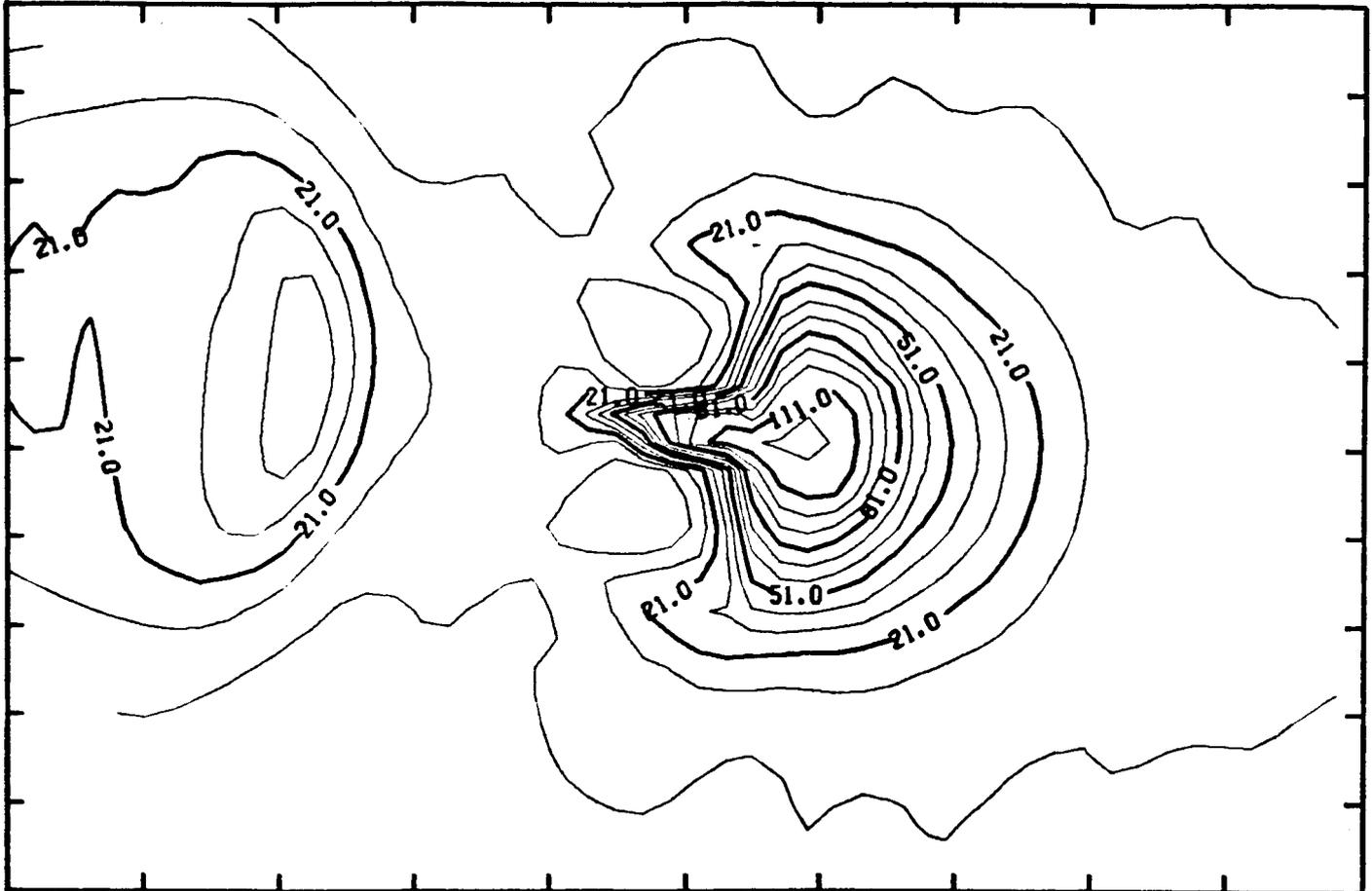
ELECTRON CONTOURS



CONTOUR FROM 50.000 TO 2150.0 CONTOUR INTERVAL OF 100.00
X INTERVAL= 0.99965 Y INTERVAL= 0.77709

FIGURE 1

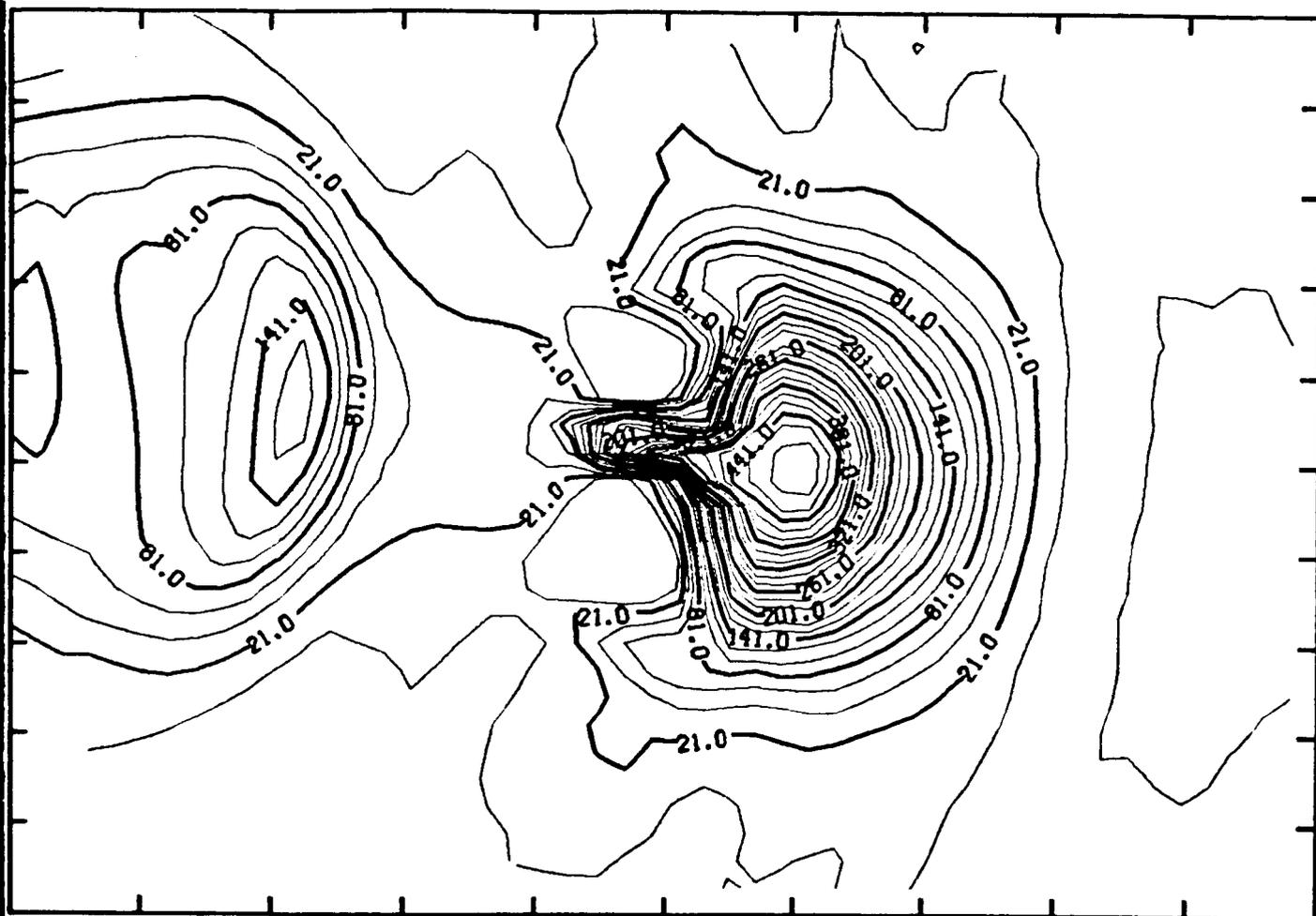
ION CONTOURS (0+)



CONTOUR FROM 1.0000 TO 131.00 CONTOUR INTERVAL 10.000
X INTERVAL= 0.99965 Y INTERVAL= 0.04271

FIGURE 2

ION CONTOURS (S+)



CONTOUR FROM 1.0000 TO 501.00 CONTOUR INTERVAL OF 20.000
X INTERVAL= 0.99965 Y INTERVAL= 0.67633

FIGURE 3

In Figures 4 and 5 we present, for example, frequency-versus-time spectrograms of Voyager data for the high band and the low band, respectively. In Figures 6 and 7 we present f-versus-t spectrograms (high band and low band, respectively) of Voyager data that has been sorted such that the sub-Io longitude is constant at 200° . Data from the ray tracing models can be directly superimposed on any of these plots for comparison. We have chosen to display sub-Io longitude = 200° because this longitude is the subject of current ray tracing studies of hectometric radiation (HOM).

ORIGINAL PAGE
COLOR PHOTOGRAPH

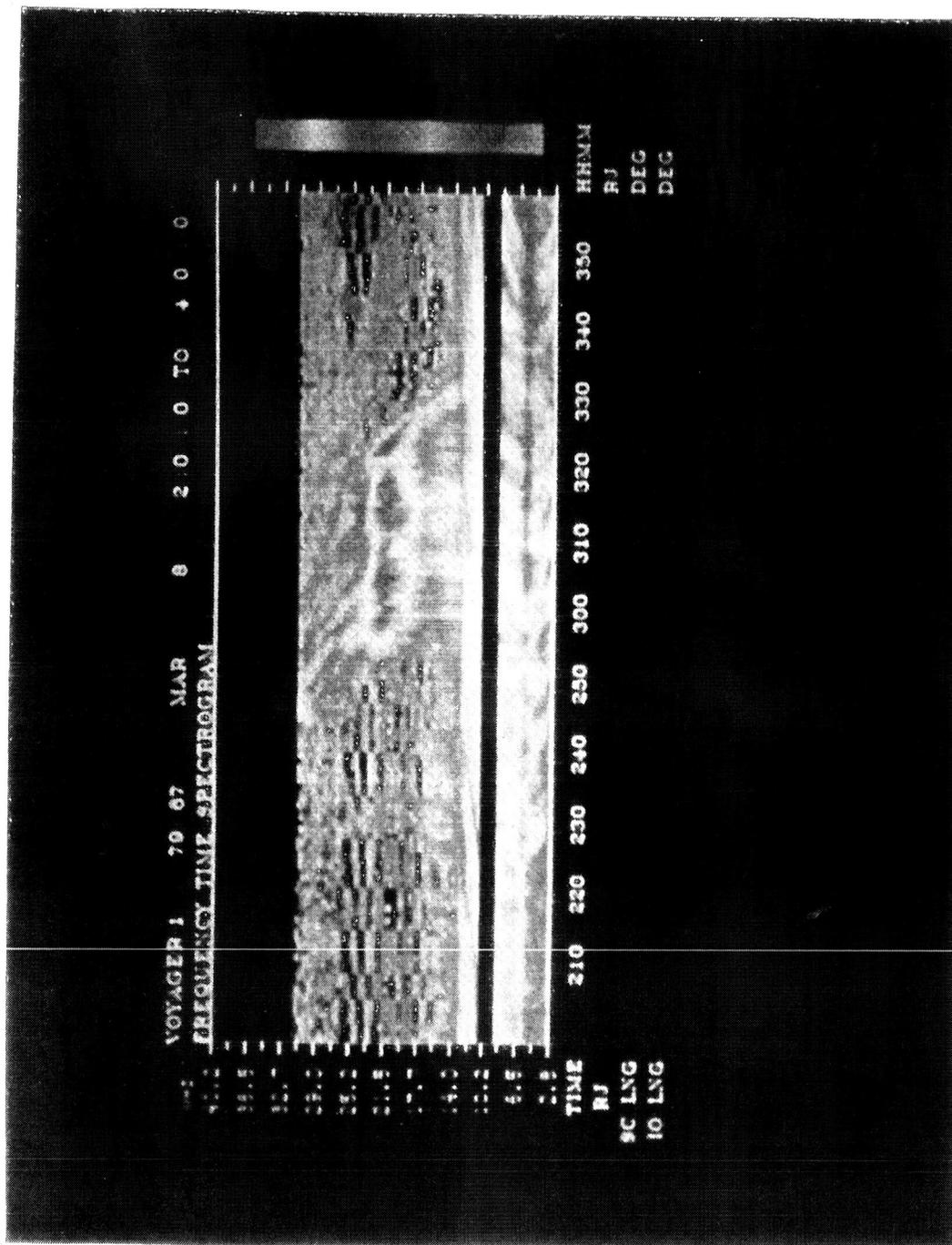


FIGURE 4

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COLOR PHOTOGRAPH

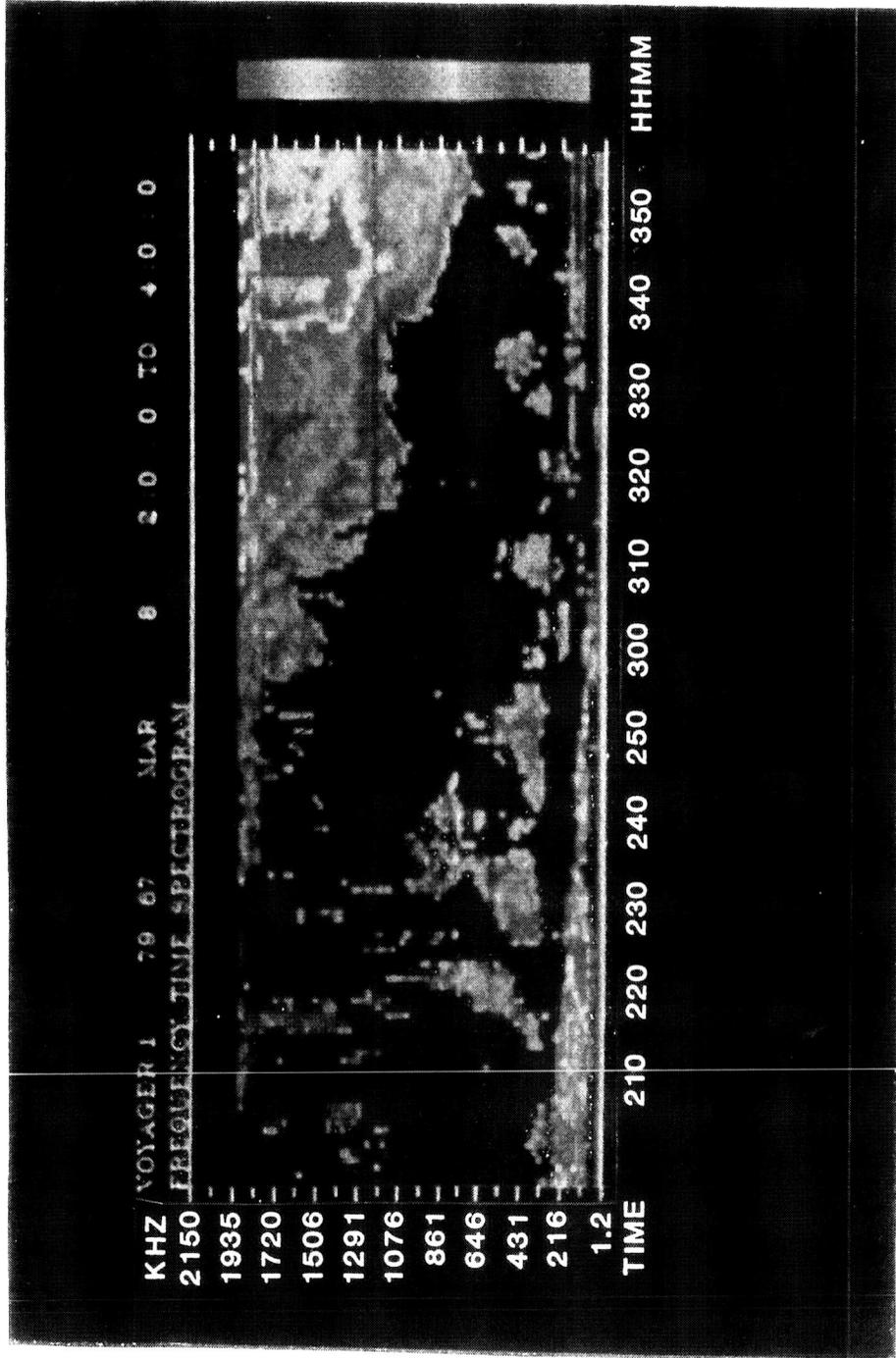


FIGURE 5

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COLOR PHOTOGRAPH

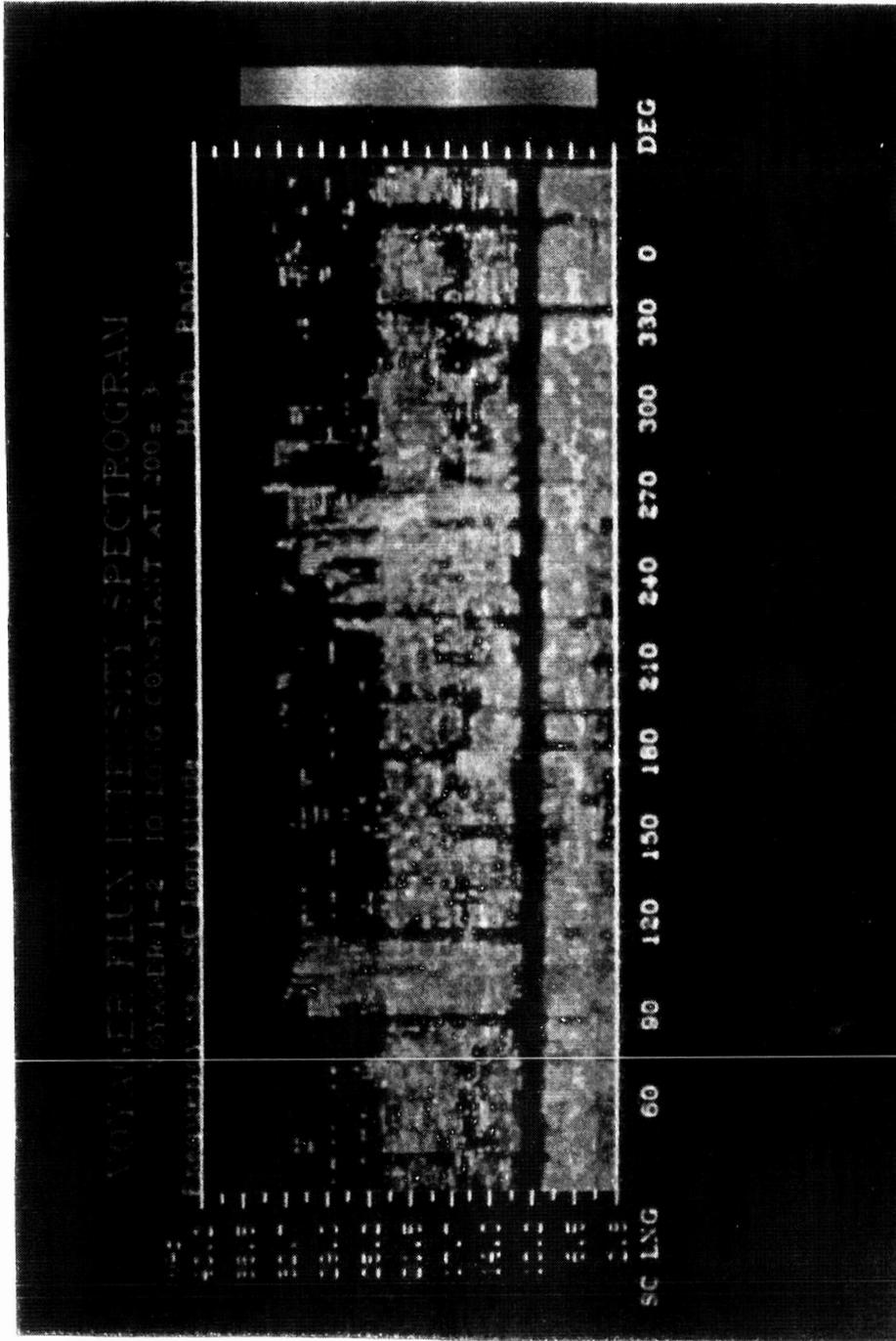


FIGURE 6

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COLOR PHOTOGRAPH

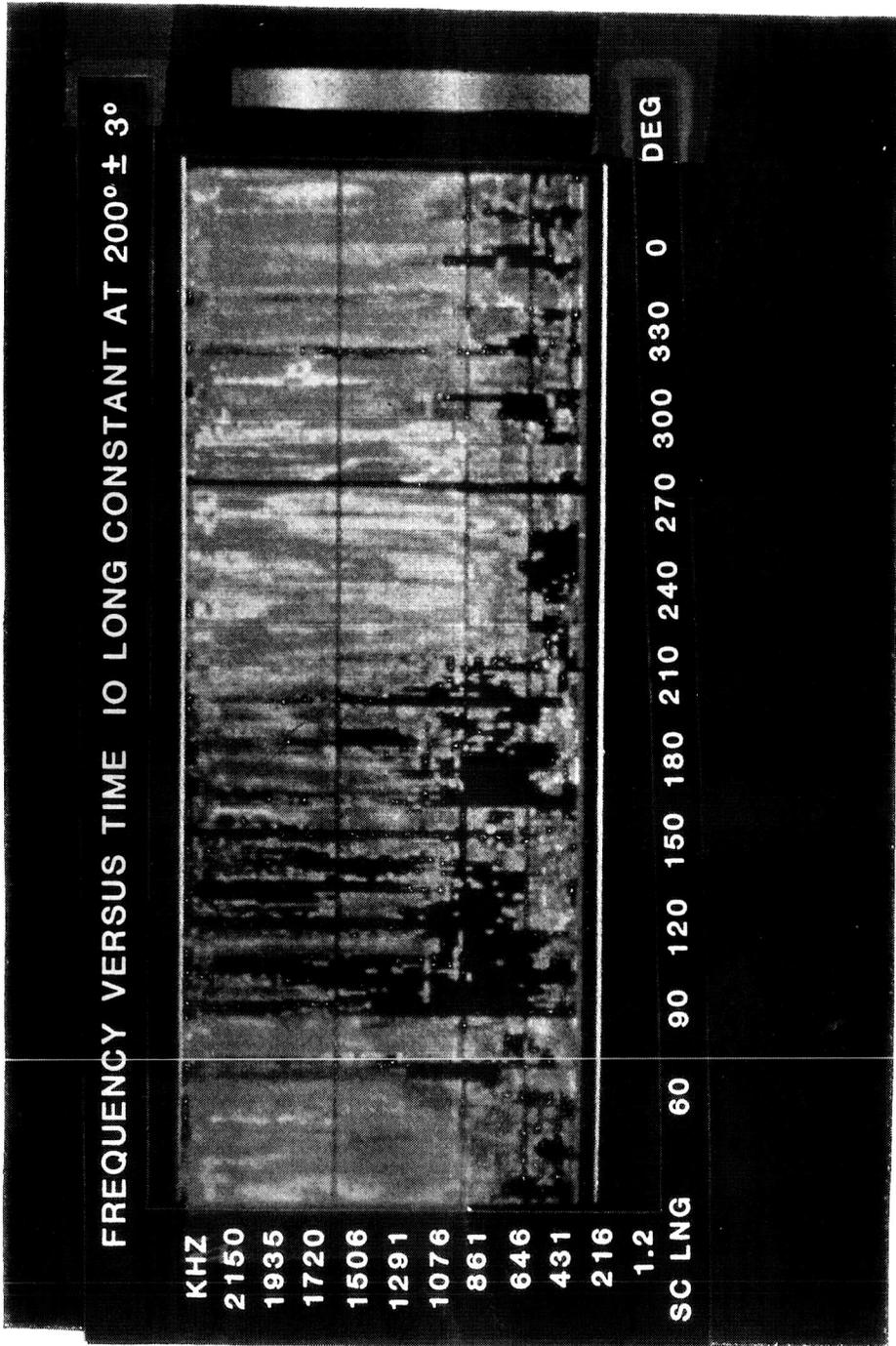


FIGURE 7

II. ON-GOING RESEARCH

One of the major accomplishments of the project has been the completion of a paper to be published in the Journal of Geophysical Research entitled: "Ray Tracing of Jovian Decametric Radiation From Southern and Northern Hemisphere Sources: Comparison With Voyager Observations". This paper, included as Appendix 1, is currently undergoing the final review process (having already been accepted by one of the two referees), and will be accepted after a few minor revisions. In this paper we demonstrate how the nomenclature "Io-dependent" and "Io-independent" sources (i.e. Io and non-Io sources) may not be accurate in all cases. We show that non-Io A emissions seem to be, at least in some cases, emitted from the foot of the Io flux tube in the southern hemisphere; we also show how Io-C emissions (thought to have a source in the northern hemisphere) may, in fact, at least partially, have a southern hemisphere source. These facts were made clear only as a result of the display of the Voyager data in the sorted, constant-sub-Io-longitude format spectrograms. These plots emphasize features which depend on the position of Io.

Currently we are in the middle of an investigation into the propagation properties of DAM emission from source regions located in the low-altitude Jovian auroral zone. It is our belief that many of the unexplained observations of Jovian DAM may result because the source region is not the Io flux tube, but particles precipitating into the Jovian auroral zone. At present we have completed ray tracing studies of eight northern and eight southern hemisphere auroral zone source regions at positions separated by about 45° in system III longitude. These studies have all been conducted at 20 MHz except for two cases which have now been completed for 4 frequencies each. Our goal is to examine each source for at least 4 frequencies each, and compare the results directly to observations of the PRA instrument. Tentative results indicate that some emission does indeed reach the satellite, but it is not clear to what extent until all the sources have been examined.

In order to be able to compare our results with the Voyager observations, we are conducting a "production-mode" sorting of the PRA data. We are creating plot files of the data sorted with respect to sub-Io longitude (as in Figures 6 and 7) for the entire circumference of Jupiter with sub-Io longitudes separated by 6 degrees. This is being performed for both the high band and the low band. The low band is particularly exciting because this type of sorting has never been done for the HOM emissions. The sorting of each sub-Io longitude requires a considerable amount of computer time, hence only a few cases can be run each day (under ideal conditions).

We are also conducting a study of PRA "close-approach" data ($r < 30 R_J$). Plots of the data sorted again with respect to sub-Io longitude are being generated for direct comparison with the data for $r > 30 R_J$. In this way the shadowing of the sources located at low altitude (such as the foot of the Io flux tube) are being examined, and a much better identification of the source region is being obtained. These results will also be presented at the symposium on the outer planets (SANBMSMOP).

The final research project we are conducting is a ray tracing investigation of HOM emissions from sources located along the Io flux tube. Because the frequencies are so low, the source positions of HOM are located

quite near the Io torus. The refractive effects of the torus on the ray path of the emissions seem to explain the frequent differences in the curvature of the HOM and DAM emissions. In other words, it appears that at least some of the HOM emission is indeed an extension of the DAM emission to lower frequencies. No new source mechanism is necessary for a portion of the HOM emission. We have ray traced emission at numerous frequencies in the high band and the low band for a sub-Io longitude of 200° . We have chosen this longitude because we have noted for this case a particularly good example of vertex-late arcs in the DAM emissions and vertex-early arcs in the HOM emissions. We hope to be able to complete this study in the next several months.

III. SUMMARY

This report represents a summary of the work completed under the NASA project, NASW-4045. We have satisfied more than the suggested goals of the work statement. It is clear, however, that we are currently in a position in which we have developed some excellent and unique software tools for the analyses of Voyager PRA data, and we are currently in the middle of several intriguing research studies, with the funding depleted. We have thoroughly enjoyed the work and present accomplishments of this project, but we hope that future Jovian and other outer planetary Voyager data analyses can be funded.

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