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A Final Report to

the National Aeronautics and Space Administration
Ames Research Center
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on Grant NCC 2-854

**Scientific and Technical Support for
the Galileo Net Flux Radiometer Experiment**

Performance Period: 1 December 1993 through 30 November 96

Submitted by

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FINAL REPORT ON GRANT NCC 2-854

Scientific and Technical Support for the Galileo Net Flux Radiometer Experiment

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I. INTRODUCTION

This report describes work in support of the Galileo Net Flux Radiometer (NFR), an instrument mounted on the Galileo probe, a spacecraft designed for entry into and direct measurements of Jupiter's atmosphere. The grant period for NCC 2-854 (as proposed) began on 1 December 1993, more than four years after the Galileo launch, covered the remaining cruise period to the time of Jupiter atmospheric entry on 7 December 1995, and extended to the time at which probe data were fully recovered and quick look analysis completed, nominally on 31 March 96. The actual award end date was listed as 30 November 1996, although the award was in support of tasks that were intended to be completed by 31 March 96. The detailed data analysis was covered by a subsequent grant beginning on 1 April 1996.

Tasks originally proposed for the post launch period covered by NCC 2-854 are briefly as follows: attend and support PSG (Project Science Group) and other project science meetings; support in-flight checkouts; maintain and keep safe the spare instrument and GSE (Ground Support Equipment); organize and maintain documentation; finish NFR calibration measurements, documentation, and analysis; characterize and diagnose instrument anomalies; develop descent data analysis tools; and science data analysis and publication. Because we had the capability to satisfy a project support need we also subsequently proposed and were funded to make ground-based observations of Jupiter during the period surrounding the Galileo arrival at Jupiter, using the Swedish Solar Telescope at La Palma, Canary Islands. The following section (II) provides background information on the NFR instrument. Section III contains the final report of work done.

II. BACKGROUND

The Galileo Net Flux Radiometer is a probe instrument designed to measure net radiation flux and upward flux in five spectral bands during descent into the Jovian

atmosphere. Solar energy deposition and planetary radiation losses from the 0.1 bar level to at least the 10 bar level were to be measured to assess the nature of radiative drive for atmospheric motions, the location and optical properties of clouds and hazes, and the amount of water vapor. (Because of a late parachute deployment the starting pressure level was about 0.4 bars.) Our Space Science Reviews paper (Sromovsky et al., 1992) describes the science objectives, instrument design, and expected performance of the NFR; detailed calibration methods and results were published in the proceedings of The Fourth Infrared Sensor Calibration Symposium (Sromovsky and Fry, 1994).

During the nearly 4-year Galileo launch delay resulting from the Challenger explosion the NFR instrument was modified to improve its performance and calibration. New detectors were procured and installed, digital and analog electronics were modified to improve optical chopping symmetry, the detector package was sealed in Xenon to eliminate both pressure perturbation noise and crosstalk, and a new bearing and bearing support fixture were installed. This ultimately resulted in a hybrid flight instrument consisting of the SN02R2 electronics mated to the SN01R2 optical head. For a detailed report of this work see the report by Sromovsky and Best (1990).

The calibration of the NFR was made especially difficult by its extremely wide spectral range, large field of view, and widely varying detector and optics temperatures. Although we were able to complete extensive calibration and characterization of the flight instrument (in non-flight configurations) prior to launch, there remained unresolved issues regarding spectral response and temperature dependence that required additional measurements of spare components and the flight spare instrument, and considerable additional analysis. Most of this was completed within the current grant period. In addition, there were inadequately characterized aerodynamic effects that had the potential to produce significant errors depending on how the mechanism varies with temperature, Nusselt number, or Reynolds number. These were not investigated due to limited resources.

Preparation for data analysis required development of radiation transfer tools for treating wavelengths from UV to far infrared, solar and planetary radiation, including emission and scattering simultaneously. In the solar channels the interpretation is complicated by strong azimuthal variations as the probe spins. We also needed to improve our spectroscopic data base of line position, strength, and shape in order to best interpret instrument measurements. Our state of progress on tasks supported by this grant is described in the following section.

III. FINAL PROGRESS REPORT

Progress summaries are provided in each of the proposed task areas.

1) Project Meetings/Project Science Support:

The PI attended the Probe Science Team Meeting held at Ames Research Center during 20-21 June 1994. Presentation of the NFR science objectives, design features, performance characteristics, and instrument status was made at the meeting. Hard copy was provided for distribution to participants with the minutes of the meeting.

The PI also attended the Probe Science Team Meetings in April 1995 and also attend the PSG and probe science meetings in July 1995, and the PSG following encounter and probe PI interchange meeting following receipt of the first 40 minutes of probe quick-look data. The PI presented NFR results at the 18 December 95 PSG meeting. The PI also attended the 26 February 1995 Probe Science meeting at GSFC, and the 19 March 96 probe science meeting in Houston (during the AGU meeting).

During the encounter period support for quick look analysis was provided by the L. Sromovsky (PI), Patrick Fry, and Andrew Collard of UW while visiting JPL (6-15 December 1995) and subsequently at Ames Research Center (16-20 December 1995). Quick-look results were presented at science team meetings and at the 18 December PSG meeting at ARC. The PI also returned to Ames to participate in the Probe press conference on 22 January 1996.

Following the encounter and NASA press conference the PI and associates participated in local (Madison, Wisconsin) TV and newspaper interviews concerning both NFR and general Galileo Project results.

2) In-Flight Checkout Support:

There were no in-flight checkouts after 20 November 1992, and analysis of that data was completed on 24 June 1993 and documented in a report by Fry and Sromovsky (1993).

3) Maintenance and Safekeeping of Spare Instrument and GSE:

During 1995 the spare instrument was removed from storage and used in a limited number of tests to investigate spectral response, temperature dependence, and electronics anomalies. These tests were performed with quality assurance oversight to protect the viability of the spare instrument for post-encounter diagnostics should that become necessary.

4) Documentation:

Software obtained from ARC for radiation transfer calculations was documented with help from Brad Sitton of ARC during his September 1994 two-day visit to Wisconsin. New calibration measurements during 1995 and analysis software

developments required significant documentation activity during the current year. Calibration files have been prepared with internal documentation contained in headers and placed on an FTP server for NFR investigator use.

5) Calibration Measurements and Analysis:

The significant improvement made in the definition of channel spectral response characteristics by reanalysis of existing calibration data was documented in papers presented at the Fourth SDL (Space Dynamics Laboratory)/USU (Utah State University) and NIST (National Institute for Standards and Technology) Symposium on Infrared Sensor Calibration, held in Logan Utah during 9-12 May 1994. To obtain maximum interaction with the other conference participants the NFR calibration was presented in three forms: a 30-minute talk, a poster, and a written manuscript published in the conference proceedings (Sromovsky and Fry, 1994). The latter was also distributed to R. Young, Probe Project Scientist, and to Co-Investigators on the NFR experiment. This paper also documents the unresolved calibration issues at that time and our approach for dealing with them.

We also completed new calibration measurements of the DTGS-T300 detector that serves as our primary spectral response reference. The spectral range from visible to mid IR (25 μm) was handled by an intercomparison measurement procured from Optronics of Orlando Florida.

The filter with known source method of spectral response measurement, used up to 45 μm for reference detector calibration, will be used to characterize filter response at wavelengths out to beyond 50 μm , and in limited system level measurements with the spare NFR under ambient conditions, using additional optics to refocus radiation passing through the filters. During this period we obtained spectral scans of needed diamond dust filters from OCLI (in May 1995). The main objectives are to better define the long wave response of channel A and define the long wave leak of the channel D filter.

6) Characterization of Instrument Anomalies:

Anomalous Offsets: We arranged for an electronics engineer to review the NFR analog circuitry to estimate reasonable offsets to be expected; he concluded that analog zero measurements with optical head flipping disabled were about as expected. But offset measurements during flipping were too high to account for as electronics errors. Spare instrument tests were carried out to investigate the source of the offsets; test procedures were written and reviewed, and tests were conducted with full quality assurance support. The first test used a covered optical head to eliminate external radiative input. The optical head was separated from the electronics and a breakout box inserted so that we could examine various possible sources of anomalous couplings that

might introduce flux offsets. The offset measured when the optical head flipping was activated was found to be independent of window heater state, blackbody power, external motor drive power, position indicator LED power, and room light intensity. Only when the optical head stopped flipping would the anomalous offset in channels B and E disappear. A second test was carried out with the optical window covered with opaque reflective tape to allow even thermal channel offset anomalies to be investigated; with this test we also recorded average analog signal traces at the preamp outputs. These were digitally processed to simulate the NFR measurements process and did show approximate agreement with the actual measurements. In the analog trace averages we did see waveforms that produced the offsets, but have not been able to identify the source; they do not bear any obvious correlation with motor current traces which might have coupled into the signal leads. A remaining possibility that we have not ruled out is low frequency microphonic effects induced by centripetal accelerations or gravitational forces, both modulated by optical head rotation.

Anomalous Temperature Dependence: We completed a test of a spare NFR preamp to determine whether the preamps have excessive leakage currents that might be responsible for the system-level responsivity roll-off beyond 40°C. Although the preamps did indicate small leakages, they were far below the levels needed to explain the responsivity roll-offs observed in the integrated flight and spare instruments.

7) Preparations for, and Analysis of, Descent Data:

A large step backward occurred in this area as a result of the 13 June 1994 death of Co-Investigator James Pollack, who had the responsibility for development of software and a spectroscopic data base for modeling thermal radiation transfer within Jupiter's atmosphere. From discussions with Brad Sitton and Richard Freedman who worked with Pollack on radiation transfer calculations, it appears that Jim was just about to begin specific adaptations to Jupiter conditions at the time of his death. Richard Freedman was tasked to carry out opacity calculations, while Sitton's role was to use these opacity files to calculate radiation fields, using a two-stream multiple scattering algorithm based on techniques described by Toon et al. (1989). In October 1994, prior to his departure from Ames, Brad Sitton visited Wisconsin, installed his software on one of our workstations, and demonstrated how to run it. The opacity files and other program data, however, were for Venus conditions, and needed to be modified for application to Jupiter's atmosphere.

The plan developed to deal with the thermal radiation modeling was to enlist Glenn Orton as a new NFR Co-I, formal approval of which is now in process, to modify and use the Sitton/Pollack code for initial sensitivity studies, supplemented by Orton's code for more exact accounting of scattering effects, although the need for more exact scattering treatment remained to be determined, and to enlist Richard Freedman to

continue his development of line lists and opacity code improvements. Glenn would provide spectroscopic advice regarding the best line data and line shape information, as well as H₂ collision induced absorption code. Andrew Collard was hired to carry out radiation transfer coordination at the University of Wisconsin, to modify the Sitton/Pollack code, to learn how to use the Freedman opacity routines, and to carry out verification tests of software by comparison with independent calculations, and to conduct sensitivity studies to guide calibration improvements and prepare for data analysis. A proposal was written and negotiated for support of Orton, Freedman, and part of Collard's work, all to deal with fulfilling Pollack's planned role in NFR data analysis and preparations associated with it. On 20 April 1995 a letter was written to Jay Bergstrahl requesting approval of Glenn Orton as NFR Co-I. A revised version, stating that no increased cost to NASA would result, was sent on 22 May. Wes Huntress approved the appointment on 8 August 1995.

On January 5, 1995, A. Collard visited M. Tomasko and Mark Lemmon at the University of Arizona to discuss the state of their code, what information was needed from us to facilitate simulation progress, and the schedule for remaining developments. We secured, with Ames assistance, tabulated descent profile information, and prepared a smoothed, gridded file of angular response data for use in the simulations.

We procured a Silicon Graphics Indy Unix workstation with approximately 10 GB of disk storage to serve as a repository for calibration data, and to serve as an environment for development of radiation transfer code and application of that code in carrying out sensitivity studies and ultimate descent data analysis. This would also serve as a repository of auxiliary data used in correlative analyses.

The Sitton/Pollack code modifications were completed and preliminary calculations made by April 1995. Freedman visited Wisconsin during 2-5 May 1995 to show us how to use his opacity code and to document his current line list. We decided not to pursue FASCODE adaptations to do Jupiter opacity calculations because earth-specific routines were embedded in a way that was difficult to modify.

To validate both the opacity and radiance calculation we decided to make detailed comparisons with the results of Carlson et al. (1993). Barbara Carlson kindly agreed to provide electronic copies of input structure and calculated spectra based on that structure. She also provided NH₃ refractive index data, originating from Fink and Sill. Comparisons with Carlson's results identified problems with NH₃ gas absorption lines in the Hitran data base. It also appeared necessary to include H₂ CIA effects in the 5 micron window (channel C) as well as at longer wavelengths. As a result of Jim Pollack's funding of Bob Gamache of AFGL to calculate H₂ broadening of water vapor lines we were able to include improved line shapes for water vapor in the May 1995 version of the line list.

During 6-7 June 1995 we met with Glenn Orton at JPL to review the status of his radiation transfer code, and to discuss absorption line parameters that should be used, issues that need to be addressed, action items, and a schedule for completion. A. Collard, L. Sromovsky, G. Orton, J. Friedson and R. Freedman attended the 2-day meeting, which was also supported by Linda Brown of JPL who provided valuable input on state of the art absorption line measurements. From that meeting we developed a plan for modifying our initial line list, to be used for a number of sensitivity studies, and for further improvements following these studies. Following the line list modifications, we started flux calculations using the same structure that Barbara Carlson provided, so that we could make comparisons with her calculations as well as between Orton's code and our own 2-stream code. Sensitivity studies included investigations of the appropriate spectral interval to use, the upper and lower atmospheric layers that needed to be included, the effects of calibration errors and uncertainties, and the sensitivity of simulated fluxes to variations in structure from the nominal model.

During 21-23 June 1995 Mark Lemmon of the University of Arizona visited Wisconsin to discuss the solar radiation transfer code developed under the guidance of M. Tomasko (NFR Co-I), to demonstrate the operation of the code on our workstation, and to carry out comparison calculations using the University of Arizona code and the UW/Sitton/Pollack/Toon code that we had modified for Jupiter applications. At that time, simulation of azimuthal variations was demonstrated. Implementation of inversion algorithms to retrieve optical depth and single-scattering albedo were also completed by the late summer 1995.

In October 1995 NFR data and retrieval simulation results were presented in a paper at the 1995 DPS meeting (Sromovsky et al., 1994)

The PI also presented Galileo results at a Colloquium for the Atmospheric and Oceanic Sciences on 5 February 1995, and a paper at the LPSC in March 1996 (Sromovsky et al., 1996a). Preliminary NFR results were also presented in the special Galileo issue of *Science* (Sromovsky et al, 1996b).

8) Ground-based Observations of Jupiter in Support of Galileo

The malfunction of the tape recorder on Galileo Orbiter resulted in the cancellation of Orbiter imaging plans to image the Galileo Probe Entry site. Given the importance of knowing what cloud environment the Galileo Probe sampled on December 7, 1995, the imaging of Jupiter from earth based telescopes was considered highly desirable. However, imaging of Jupiter in November and early December was made difficult by the proximity of Jupiter to the Sun (about 9°). Indeed, much of the observing would have to be performed during the day. (The Hubble Space Telescope cannot point to an object if the sun angle is less than 45 degrees.)

In this context, the availability of the Solar Telescope of the Swedish Royal Academy of Sciences on the island of La Palma, Canary Islands was particularly attractive. Through a collaboration between the Uppsala Astronomical Observatory and the Space Science and Engineering Center of the University of Wisconsin-Madison, access to the telescope was granted to the Space Science and Engineering Center for planetary observations (as per communication from Prof. Hans Rickman, 1995).

Primarily, the support consisted of travel to the telescope site and analysis of the acquired data and to make it speedily available to the Galileo investigators. Mr. Johan Warrel from Uppsala, Sweden, S.S. Limaye (UW-Madison) and Mr. Uri Carsenty from DLR (Berlin, Germany), provided overlapping coverage to satisfy the safety requirements of having two observers present while carrying out the Jupiter observations during a 14 day period beginning about 26 November 1995. The results of the imaging effort were presented in the Galileo Special Issue of Science (Orton et al, 1996).

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ACRONYMS

NFR Net Flux Radiometer

SN01R The NFR unit that was installed on the probe ready for launch in May of 1986. It was delivered to UW in December 1987 for verification of the planned NFR Calibration tests.

SN01R2 The NFR unit that was upgraded from SN01R in February 1989. The SN01R2 optical head is on the Probe in transit to Jupiter. The SN01R2 electronics are mated with the defective SN02R2 optical head and reside at UW.

SN02R This unit is the design equivalent of the SN01R instrument. The SN02R unit was initially delivered to UW in August 1987 for verification of the planned NFR Characterization tests, then returned to Martin Marietta for upgrading to SN02R2.

SN02R2 The upgraded SN02R NFR unit. This unit was to be the flight unit and was delivered to UW for Characterization and Calibration testing on October 1988. The tests revealed a failed detector package seal. The defective SN02R2 unit was installed on the Probe in October of 1989. The SN01R2 optical head later replaced the defective SN02R2 optical head on the Probe. The flight configuration that traveled to Jupiter is the SN02R2 electronics with the SN01R2 optical head.