THE FIRST/SMIM INTERNATIONAL, COLLABORATION*

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Abstract

The paper discusses the reason why submillimeter astronomy is important, why it must be done from space, and what we can expect to discover from this field of astronomy. It follows the plans for submillimeter missions developed in Europe and the United States, how they evolved over time, and how' the two communities came together to urge a joint mission to explore the submillimeter. The possible involvement of the United States in a joint mission is explored and the advantages to the U. S. scientific community is examined. The technology required for such a mission is defined and the current state- of-the-art evaluated. Finally, the improvement to the mission with U. S. participation is shown.

Nomenclature

CNES	Centre National d'Etudes Spatiales, the French space agency
DSN	Deep Space Network
FIRST	Far Infrared and Submillimetre Space Telescope
h	Plank's constant
k	Boltzmann's constant
LDR	Large Deployable Reflector
MAU	Million accounting units
PSR	Precision Segmented Reflector
SIRTF	Space Infrared Telescope Facility
SIS	superconducting-insulating-superconducting
SMILS	Submillimeter Imager and Line Survey
SMIM	Submillimeter Intermediate Mission
SMME	Submillimeter Explorer
ν	Frequency

1. Background

The submillimeter region of the electromagnetic spectrum holds the key to some of the most important aspects of astronomy. These range from star-forming, molecular clouds and protoplanetary disks in our galaxy to infrared emitting galaxies at cosmological distances. Indeed, the essential problems of star-formation and galaxy-formation will be directly probed by the submillimeter spectral lines and continuum radiation emitted by these objects. Figure 1 shows the richness of the expected spectrum of a typical molecular cloud at a temperature of 30 K.(')

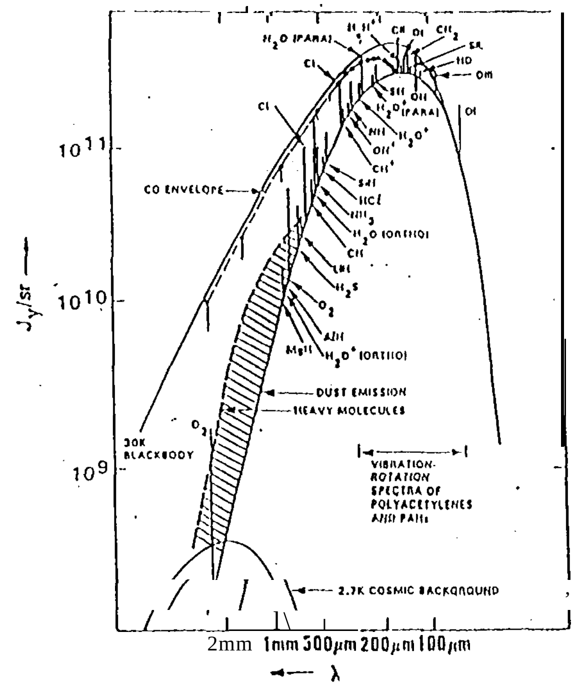

Figure 1. Dense Interstellar Cloud Spectra

While windows of transmission for submillimeter radiation exist at the best Earth sites, they cover only a small portion of the submillimeter. Even airborne observations on the KAO have numerous gaps in the possible coverage. Figure 2 shows the transmission in

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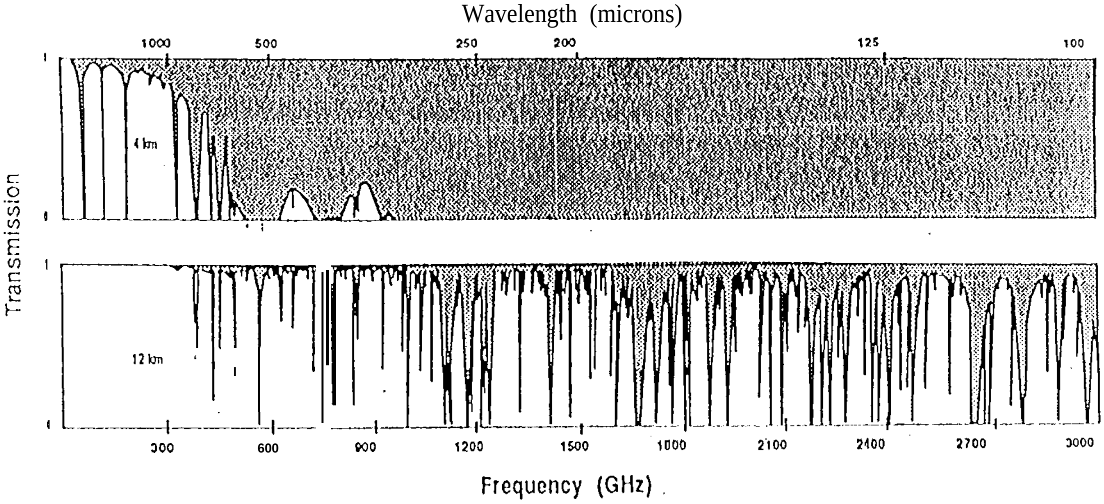

Figure 2. Submillimeter Atmospheric Transmission

the submillimeter region from a 4250-meter mountaintop site and for the KAO at an altitude of 13 700 meters.(1)

In 1979-80 the Decade Committee for Astrophysics (Field Committee) recommended submillimeter space mission with an telescope aperture of 10 to 20 meters and covering the spectral range from 30 µm to 1 mm. This Large Deployable Reflector (LDR), shown in Figure 3, would perform both spectral and continuum observations.(2) This telescope would be assembled in space (possibly on the Space Station) and be boosted to a higher operational orbit. Between 1981 and 1984 a series of NASA contractor studies were performed on the LDR concept which found that glass panels were too heavy and the cost of the mission too high.

In 1984 a technology development program was defined to develop lightweight panels, and local oscillators and superconducting-insulating-superconducting (S1S) detectors. The goal was to develop a segmented telescope (required for on-orbit assembly) with an areal density of less than 10 kg/m^2. The frequency range of the S1S heterodyne receivers, and the local oscillators to support them, should be extended from the current 200 GHz range to around 1200 GHz to obtain the spectral resolution required for a meaningful spectral survey.

In 1986 a proposal was made under the Explorer program for a submillimeter mission with a 4-meter aperture.(3) This mission, to be launched on the Space Shuttle, was the first choice of the IR/Radio branch of NASA's Astrophysics division, The Challenger accident, however, eliminated the Shuttle as a possible launch vehicle for Explorer missions, which were limited to Delta or smaller launch vehicles.

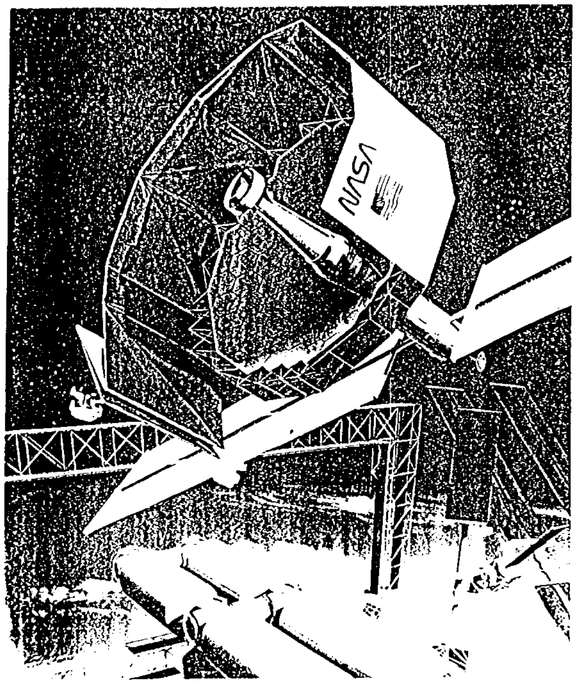

Figure 3. Large Deployable Reflector (LDR)

By 1989, the LDR study was redefined to look at a smaller mission that did not require on-orbit assembly, This resulted in two options: the

Submillimeter Explorer (SMME) with a 2.5-meter aperture to fit on a Delta launch vehicle and a 3.67-meter aperture Submillimeter Imager and Line Survey (SMILS), to fit inside an Atlas shroud.(4) These alternate missions were to fit into a "moderate mission" category. Within a year the "moderate" line had been reduced to an "intermediate mission" category limited to a Delta-class launch vehicle, at which point the mission was renamed the Submillimeter Intermediate Mission (SMIM), shown in Figure 4. This mission was selected by the new Decade Committee (Bahcall Committee) as the next astrophysics mission after SIRTF.

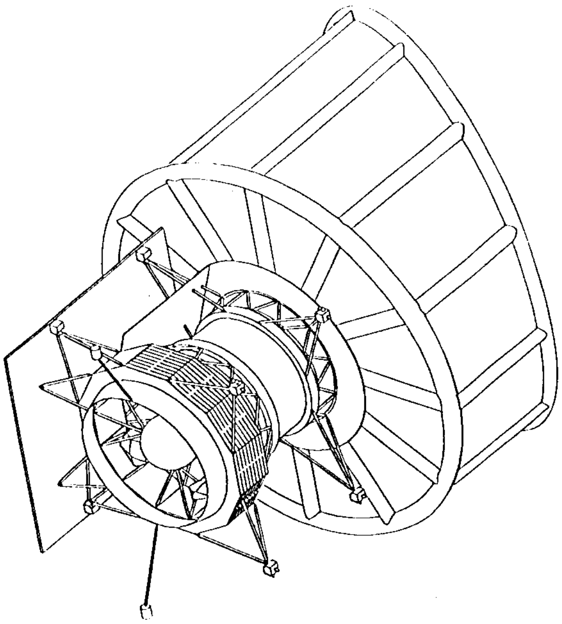

Figure 4. Submillimeter Intermediate Mission

. About the same time that NASA was conducting contractor studies of LDR, a Far Infrared and Submillimetre Space Telescope (FIRST) was being proposed in Europe. This mission, to be launched on an Ariane, had a deployable 8-meter aperture and had many of the same goals as LDR.(5) In 1989 FIRST was accepted as one of the cornerstone missions of the Horizon 2000 program that defined ESA's goals for the rest of the century, At that time the mission costs were capped at 400 MAU (1984). The initial FIRST configuration is shown in Figure 5. In 1990 evaluation of the FIRST costs showed that the mission would exceed the cost cap and it was descoped to a 4.5-meter, non-deployed aperture (the maximum diameter possible inside an Ariane V shroud).(6)

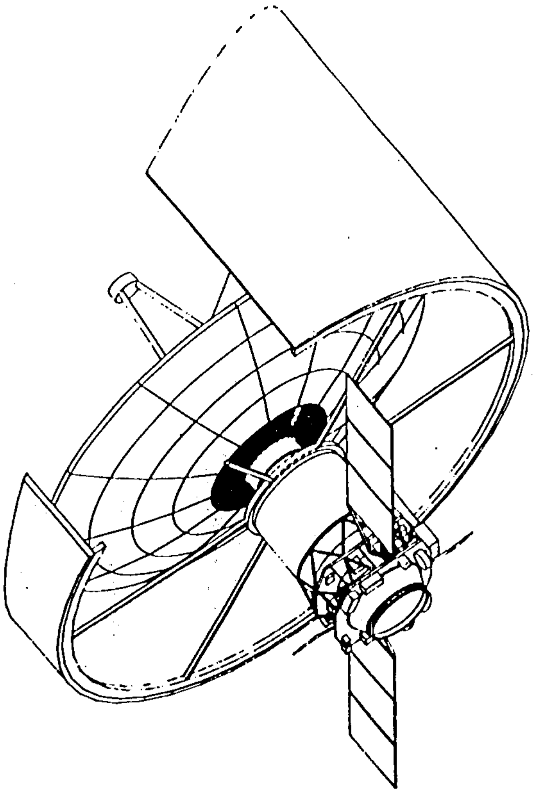

Figure 5. Far Infrared and Submillimetre Space Telescope

The International Astrophysical Union held a Colloquium a Liege, Belgium in July, 1990 on "From Ground-Based to 'Space-Based Sub-mm Astronomy". At this colloquium Tom Phillips, chair of the NASA Submillimeter Science Working Group and Reinhard Genzel, chair of the FIRST Science Advisory Group, proposed that NASA and ESA collaborate on a single mission. This concept was strongly supported at the colloquium and among the other members of the submillimeter astronomy community to which it was distributed (around 200 scientists). At that time, NASA showed some interest in a collaboration but ESA appeared more interested in a European mission.

Both agencies continued technology development efforts and mission studies to improve the mission definition. By 1992 ESA had to further descope FIRST to a 3-meter aperture to reduce costs.(7) Even at that size, it appeared that it would be difficult to meet the cost cap. At the same time, it was apparent that funds would not be available for a SMIM new start before the turn of the century. At that point ESA asked NASA if they were still interested in a collaborative mission. In 1993 NASA and ESA agreed to interactions between FIRST and SMIM at both the science and mission levels to investigate collaboration options. NASA provided ESA with a series of possible contributions to FIRST. These included increasing the aperture to 4 .S-meters and providing panels for the telescope, providing a cryostat, moving the mission to a heliocentric orbit with DSN tracking and data acquisition support, and providing the heterodyne instrument. ESA was interested in a commitment from NASA to participation in FIRST, but NASA was not able to identify a funding wedge to support the mission on the schedule planned by ESA. Later in 1993 ESA selected Rosetta as the third and FIRST as the fourth cornerstone mission, delaying initiation of FIRST for three years. This schedule offers a better chance of a budget wedge for support of FIRST, but NASA is still not in a position to make a commitment.

11. Technology Development

S1S Heterodyne Receivers

The important figure of merit for a heterodyne receiver system is the receiver noise temperature. The lower the noise temperature, the more sensitive the receiver. The lowest noise temperature achievable is determined by quantum fluctuations. This limit, known as the quantum limit, corresponds to an equivalent noise temperature of

$$T = h\nu/k \qquad (1)$$

where h is Planck's constant, v is the frequency, and k is Boltzmann's constant. The emphasis for the astrophysics applications is to produce components that will result in receivers with performance better than 10 times the quantum limit. At the initiation of NASA's sensors program performance between 5 and 10 times the quantum limit had been achieved for frequencies up to about 200 GHz. Progress with niobium (Nb) S1S tunnel junction mixers is shown in Figure 6. In 1994 the FIRST requirement of 20 hv/k has been achieved up to 750 GHz. The remaining challenge is to extend this performance to 1.2 THz for the S1S receivers. Several approaches are under investigation at the current time, including the use of niobium nitride(NbN) mixers, which have a higher gap frequency than Nb, use of improved circuits, and Nb hot electron bolometers, which do not demonstrate a frequency dependence in noise temperature.

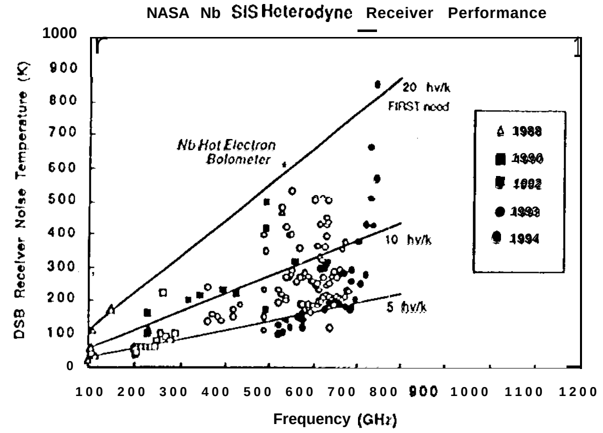

Figure 6. S1S Mixer Performance as developed by NASA's Submillimeter Sensor Program, October 1994

The other goal of the sensors program are to develop planar varactor multipliers in the 400 to 1200 GHz range. These multipliers have been demonstrated up to above 300 GHz with sufficient power to drive S1S mixers. The alternative whisker contacted multipliers have been demonstrated to 800 GHz, but the use of planar devices will significantly reduce both risk and cost for the local oscillator systems,

Lightweight Optics

Similar progress has been made in producing lightweight optics for use in the submillimeter. The goal of the optics program is to produce a primary reflector with an areal density of <10 kg/m². The backup structure should weigh no more than the primary reflector. The material selected for the primary reflector was initially graphite-epoxy with a face sheet, a composite honeycomb core, and a backing sheet. A composite support structure was also baselined. More recent efforts have used graphite-cyanate for the reflector and core to reduce microcracking and moisture absorption, Current mass values for a segmented reflector are -7 kg/m² for the reflector surface and for the support structure. Some reduction in the support structure mass may be possible if a monolith is used instead of a segmented reflector,

10 be diffraction limited, the total surface figure of the system should be on the order of 1/1 O of the minimum wavelength to be observed. For the submillimeter this requires a total surface figure of less than 10 μm.

Given the other errors in the overall optical system, the RMS surface accuracy of a segmented primary reflector should be ≤3 μm. Based on the initial goal of a 10 - 20 meter reflector, the optics program concentrated on a segmented primary consisting of 1-meter panels. (The requirement for a monolithic primary would be an RMS surface accuracy of about 4 pm.) Figure 7 shows the progress that has been made in producing smooth panels since the inception of the optics program.

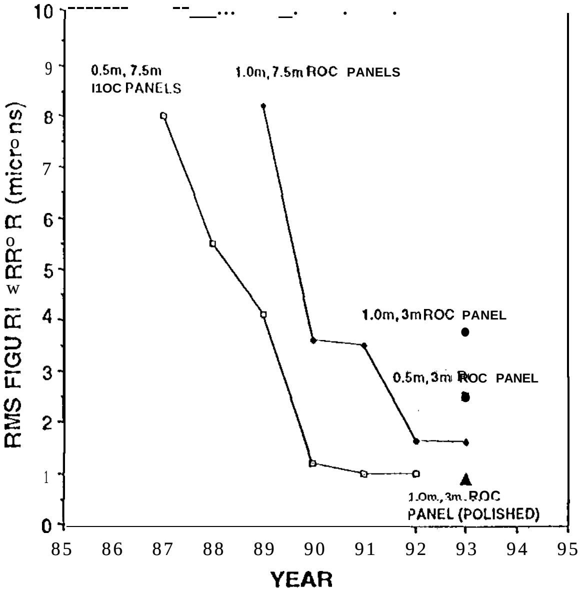

Figure 7. Composite Panel Manufacturing Precision

III. Current Status

At the present time both ESA and NASA are working toward a collaborative mission. The details of just what the collaboration will be, the schedule for commitment, and how the viewing time will be shared are not yet determined. The major effort now is to look at the possible NASA contributions to the mission and see if they both reduce the costs to ESA sufficiently and if they can result in a better mission than either agency could stage independently.

Current FIRST Baseline

The FIRST mission is planned for a 24-hour elliptical Earth orbit, 1000 x 70 500 km, with viewing taking place above 40000 km. The initial estimate of the required superfluid helium cryostat for FIRST was 3200 liters. Concern over the size and mass of the cryostat (ESA projects include launch vehicle costs as part of project costs) led to a new baseline utilizing mechanical refrigerators. The baseline is for 13 Stirling-cycle refrigerators (8 active and 5 redundant) with Joule-Thomson (J-T) stages to achieve 4 K. Sub-Kelvin temperatures for bolometers would be the responsibility of the payload. The primary aperture diameter is 3 meters as mentioned above. The baseline FIRST configuration is shown in Figure 8.

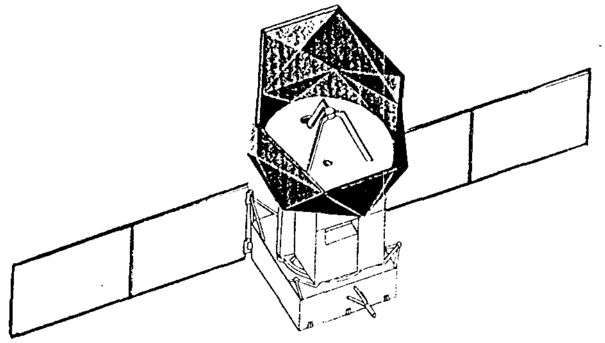

Figure 8. FIRST Configuration

The large solar array is required to provide 860 W at end-of-life to the mechanical refrigerators in addition to the other power requirements of the spacecraft. Data return is planned for real-time during the approximately 17 hours/day that the spacecraft is above 40000 km. The instruments complement consists of a multi frequency heterodyne instrument covering the frequency range from 490 to 1130 GHz and a direct detection instrument performing spectroscopy from 90 to 300 μm and photometry from 90 to 900 pm.

Potential Collaboration Options

The FIRST mission currently has a funding problem of on the order of $ 100M. ESA has told the project that it shouldn't descope the mission any further, so it is looking for a partner to offset some of the mission costs. ESA accounting is somewhat different than NASA'S. While the project pays for the launch vehicle, unlike NASA it does not provide the scientific payload. That is done by national space agencies. Thus, providing the heterodyne instrument does not reduce ESA's project cost. At the same time, any increase in spacecraft mass increases the launch costs to them. ESA has suggested that two areas where collaboration could be considered would be the telescope and the solar array, These areas would minimize interface problems while allowing ESA to distribute their portion of the costs among their member states, The science community that has been involved with the NASA submillimeter planning would also like to enhance the mission, by increasing viewing time and aperture area. The specific approaches to collaboration that have been under study are described below.

Telescope. The United States is in a very strong position in composite telescope technology. A major effort has been made under the Precision Segmented Reflector (PSR) program to develop methods of producing composite panels that demonstrate good surface, thermal, and lifetime properties. The panels produced have undergone testing down to 150 K and show excellent thermal stability. Microcracking has been significantly reduced by replacing epoxies with cyanates, which also reduces the moisture absorption of the material. Thermal studies have indicated that temperature uncertainties and variations in orbit do not cause significant figure variations.

The major questions remaining have to do with the size of the telescope and selection of a monolith or a segmented reflector. The current baseline for FIRST is for a 3-meter monolith that does not meet the goal for diffraction limited viewing at the shortest wavelengths. The submillimeter science community in the United States would like a 4-meter telescope that is diffraction limited. Studies are underway to determine whether a 4-meter monolith with the required surface smoothness is possible or if a segmented approach would be better. The NASA contribution could consist of the entire telescope assembly, including the sunshade and star trackers,

Mission Design. FIRST has selected the 24-hour elliptical orbit as the baseline trajectory. The advantages of this orbit are reasonable energy requirements for transfer from a geosynchronous transfer orbit, a relatively long viewing period (above the Van Allen belts) in each orbit, short communication range for data acquisition, and a reasonably stable ground track to simplify tracking. Negative factors the radiation environment traversed twice each day, the thermal variation around the orbit, solar occultations, and the need to avoid earth and lunar radiation on the telescope.

Alternative orbits were investigated for the earlier SMIM studies, concentrating on a heliocentric orbit that would just lead or lag the Earth's orbit at 1 au. This orbit recedes from the Earth at a rate of about 0.1 au. per year. For FIRST, a halo orbit around the L_2 libration point of the Sun-Earth system would provide all of the advantages of the heliocentric orbit without the long communication ranges of the lead or lag orbit. A typical halo orbit is shown in Figure 9.

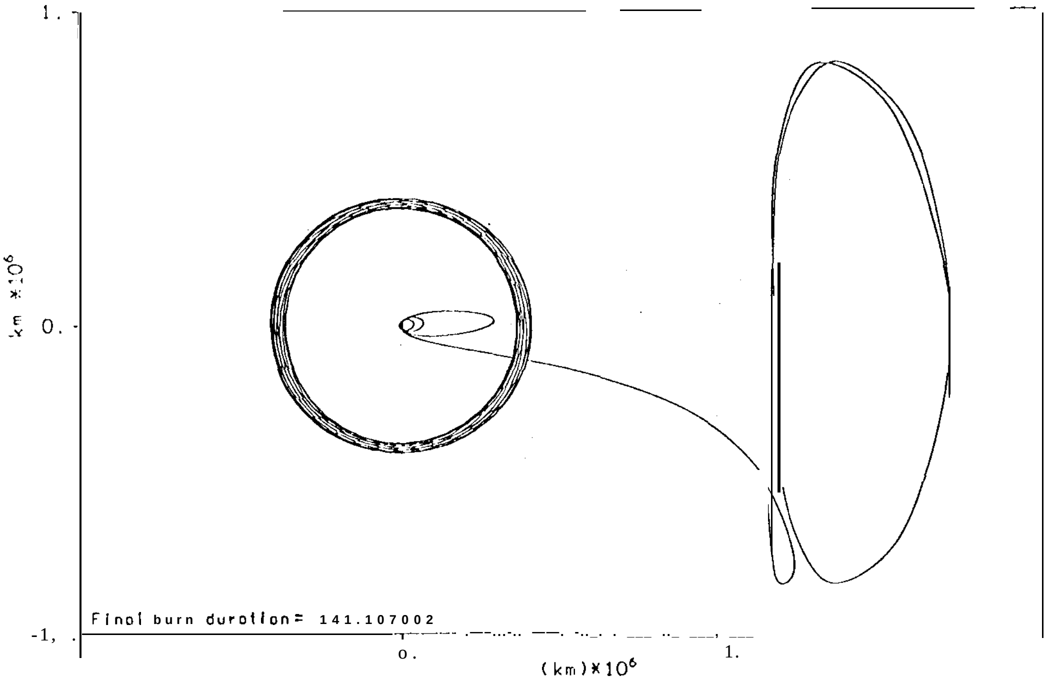

Figure 9. halo Orbit Around L_2

This orbit requires very little station-keeping propellant and provides a stable thermal environment while avoiding the high-radiation levels of the Van Allen belts. Viewing time is available 24 hours/day.

Studies for SIRTF have shown that very low temperatures can be achieved in either the L_2 or heliocentric orbits. By proper shielding and the use of passive radiators on the anti-Sun side, temperatures of 60-80 K are readily achievable. While high spatial resolution is more important that reflector temperature in the submillimeter, as opposed to the infrared, a colder telescope contributes less background radiation to the direct detection instruments.

Mission Operations. If the L_2 halo orbit is used for FIRST, the real-time data acquisition baseline is no longer viable. The longer communication range requires the use a medium-gain antenna on the spacecraft and larger receiving antennas. NASA could provide support with the DSN 34-meter network which would be adequate for high-rate data acquisition. On-board solid-state data recorders would be used and the data dumped to Earth once a day, probably over the Madrid DSN station.

Cooling System. The baseline FIRST cooling system consists of 8 active coolers and 5 redundant coolers. The payload module is enclosed by a shield that is passively cooled to 150 K (some additional cooling is provided by the intermediate stage of two-stage 20-50 K Stirling cycle coolers). Three single-stage Stirling cycle 50-80 K coolers cool an inner shield to 65 K. Two of these are active and one redundant. Each instrument is then enclosed in a 20 K box, each cooled by 3 of the 20-50 K coolers (2 active and one redundant for each instrument box). Finally, each instrument is cooled by two (one active and one redundant) 4 K coolers consisting of 20 - 50 K two-stage Stirling cycle precoolers and a closed Joule-Thomson cooler.

An analysis has been performed to optimize the cooling system on FIRST(*). Several elements go into simplifying the system and improving its performance. First, using the L_2 halo orbit would allow eliminating the three 50 - 80 K coolers since the desired temperature could be obtained passively. Second, a technique has been developed to use a heat interceptor increase, the capacity of the 20-50 K coolers by a factor of 2, using the 65 K shield as a heat sink, This would reduce the number of operating coolers by two (one for each instrument). Finally, use a 10 K hydrogen sorption cooler in place of the Stirling cooler as a precooler for the Joule-Thomson increases its efficiency by a factor of three due to the lower temperature achievable (8 -10 K vs. 17 K). Thus one hydrogen sorption cooler can cool the Joule-Thomson coolers for both instruments, eliminating one active and one redundant Stirling cooler,

An additional advantage of the hydrogen sorption cooler is its lack of moving parts. The 4 K precooler must be located very close to the instruments to reduce parasitic heat loads. A potential problem exists for the bolometers used in the direct detection instrument due to vibration of the Stirling cycle coolers, The S1S instrument may be sensitive to the cyclic magnetic field produced by the Stirling compressor. Neither of these effects are present with a hydrogen sorption cooler.

Thirteen cooler are reduced to 6 of which 3 are active. The effect of the improved cooling system also significantly reduces the power requirements on the spacecraft. As a result. the additional propulsion mass needed to reach the L_2 halo orbit is more than offset by savings in the cooling and power subsystems.

S1S Heterodyne Instrument. Perhaps the greatest advantage for the United States of collaborating with ESA on FIRST will be the opportunity to lead in the provision of the heterodyne instrument, The Submillimeter Sensors program funded by NASA has placed the United States in the forefront in this field. The current concept is to collaborate with the leading European heterodyne instrument developers under U. S. leadership. This would provide an significant role in the core science program for the mission and open the door to the entire submillimeter community in the United States to participate in the larger peer-reviewed program.

Other Elements. ESA has expressed interest in NASA providing the solar array for FIRST. Such a collaboration has the advantage of minimum interfaces with the ESA-supplied spacecraft. It is also possible that bolometers for the far infrared direct detection instrument would be obtained from the United States by the national space agency that provides that instrument.

IV. Summary

NASA has seriously considered a submillimeter mission. This is a region of the electromagnetic spectrum that is largely closed to us on Earth. There is much to be learned about our universe. But, the cost is large. In today's environment there is just not the money to do what we would like to do. The best cost determined for a one-year mission, with a 2.5-meter telescope, was about $400M. By collaboration there is an opportunity for a much better mission, with up to six years and a 4-meter class telescope. This is possible because ESA has committed to a major mission and wants our help. Our best estimate is that the cost to NASA would be less than $ 150M for a truly world-class mission, This meets the goals of more science for less money and cooperation with our space-faring friends. HSA is moving on a schedule that releases an Announcement of Opportunity for the scientific instruments in 1997. Selection would occur by the end of that year. It is planned to demonstrate the technologies required for the mission by the end of 1998. The tentative schedule for FIRST is shown in Figure 10. This is an opportunity for the United States to carry out the high priority goals stated in both the Field and Bahcall reports with a much reduced investment.

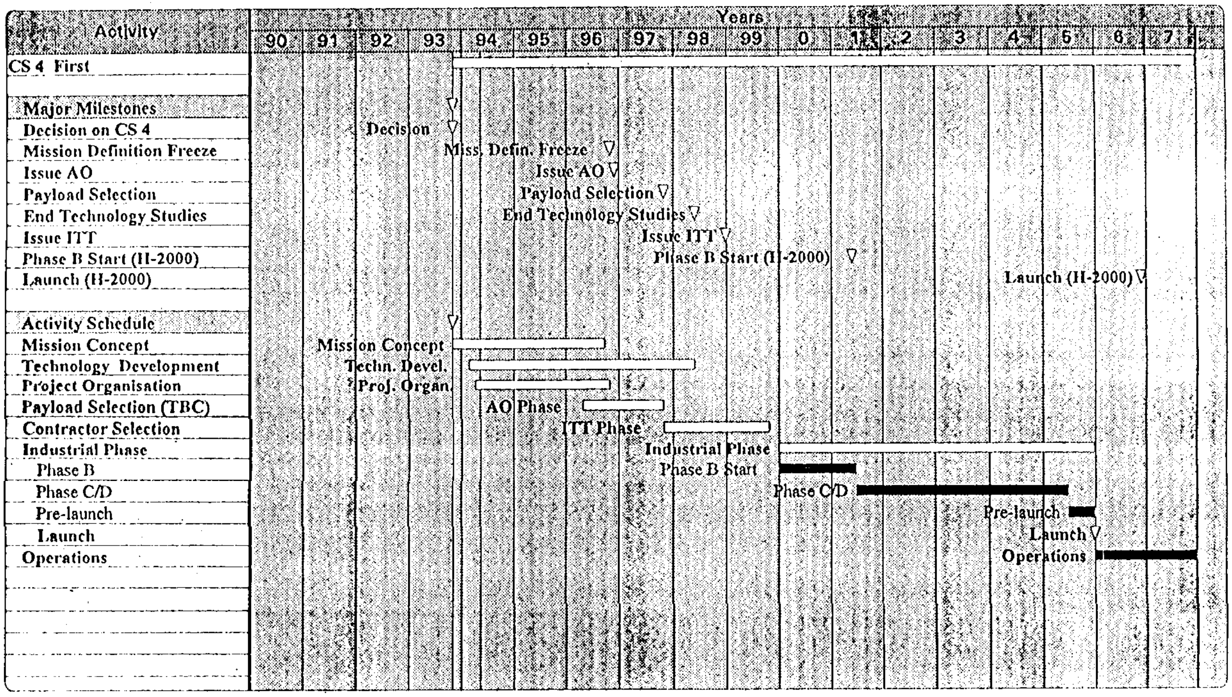

Figure 10. Tentative FIRST Schedule

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