BOMEM

NGST

Next Generation Space Telescope

Final Report

Volume 2 - Planning Report

Document Number:	**SP-BOM-006/99**		
Issue:	**1**	**Revision:**	B
Issue Date:	**13 October 1999**	**Document Name:**	Annex B2 .doc

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DOCUMENT CHANGE RECORD

Issue	Rev.	Date	Chapter/Paragraph Number, Change Description (and Reasons)
1(draft)	-	25 March 99	Draft of document
1	-	6 April 99	First release of document
1	A	28 sept. 99	Modified version to remove references to cost and schedule to include in the final report to NASA.
1	B	13 October 1999	New revision to remove proprietary notices.

1. INTRODUCTION

1.1 BACKGROUND INFORMATION

The Next Generation of Space Telescope (NGST) project of NASA is intended to provide continuity and new focus for research following the success of the Hubble Space Telescope. It is considered to be a technologically challenging project as the technology needed is not necessarily available. It challenges the innovation of the scientific and technological community to come up with an affordable technology to carry out the scientific goals of the mission.

Canada has a strong Space Astronomy community and they have ranked the participation of this project as the priority in their LTSP III submission. In order for Canada to participate, the areas of technical expertise and competence necessarily has to match the required technologies of the NGST project. The nature and scope of the Canadian contribution to the NGST are neither identified nor defined. The CSA sees the Canadian contribution as one that matches the industrial capability, an area that would result in industrial and economic growth and provide a sound base for competitiveness in the international market.

At the end of 1998, CSA awarded a number of contracts to Canadian firms. Bomem was awarded such a contract to study the potential use of a Fourier Transform Imaging Spectrometer as a science instrument for NGST.

1.2 SCOPE OF PROJECT

This work was carried out under contract no 9F007-8-3007/001/SR.

Bomem proposed to study the potential use of a Fourier Transform Imaging Spectrometer as a moderate spectral resolution camera for NGST. The approach was to first investigate the trade space of the instrument design. Next the performance of the instrument was predicted to confirm the suitability of the technology for the NGST mission. The risk analysis and mitigation plans were then completed. Finally the Cost and Schedule estimates were drafted based on the previous findings.

1.3 SCOPE OF DOCUMENT

This document is Volume 2 of the final report. The deliverables of the study contract are listed in Table 1.

Volume 2 covers the scheduling and cost estimates of the Canadian participation proposed by Bomem for the NGST program. This participation is described in Section 2. This report also includes the risk assessment and mitigation plan to support the level of effort proposed and described in Section 4.

Table 1: Deliverables of the study contract

Volume	Document Number	Document	Description
1	SP-BOM-005/99	Executive Summary	5-page summary of the findings of the contract
2	SP-BOM-006/99	Planning Report	Report on the scheduling and cost of the proposed Canadian participation. The planning report also includes the risk assessment and mitigation plan
3	SP-BOM-007/99	Trade Analyses	Report on the trade analyses performed to arrive at a credible baseline for the proposed Canadian participation.
4	SP-BOM-008/99	Performance Analyses	Report on the sensitivity analyses performed to evaluate the suitability of the proposed Canadian participation for NGST
5	SP-BOM-009/99	Technology Report	Report on some proposed novel technology approaches to the specific NGST environment for the proposed Canadian participation.

1.4 PROJECT METHODOLOGY

Figure 1 shows the structure of the project as it was presented in the Bomem proposal (see RD 1). This work flow was followed remarkably closely during the execution of the project. The labels on the left hand side of the boxes in Figure 1 refer to the items requested by the government in Section 2 of the statement of work. As can be seen a number of additional tasks were added to complement and enhance the suggested work.

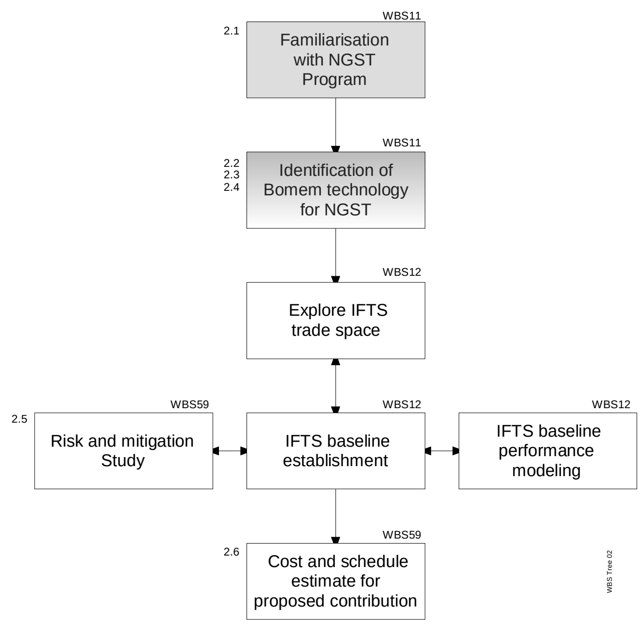

Figure 1 Structure of the Bomem lead study contract.

In the task "Explore IFTS trade space", we explored the trade space of the NGST IFTS to finally arrive at a technical baseline. The results of the trade studies is described in RD 2. This technical baseline raises the fundamental design issues on one hand and proposes a baseline with a representative level of complexity of the final instrument on the other, with enough details to be able to build a realistic cost and schedule estimate.

The spectrometric performance of this baseline was evaluated to verify compliance with the science requirements. The results from the simulations can be found in RD 3.

Next a risk analysis was performed and a mitigation plan was drafted (see Section 4). Finally the cost and schedule estimates were produced and are described in Sections 5 and 6.

1.5 REFERENCE DOCUMENTS

RD 1 Bomem Proposal No:SPIR180898, issue 1, revision -, dated 8 September 1998, in response to solicitation No 9F007-8-3007/A.

RD 2 Volume 3 - Trade Analyses, SP-BOM-007/99

RD 3 Volume 4 - Performance Analyses, SP-BOM-008/99

RD 4 Volume 5 - Technology Report, SP-BOM-009/99

2. PROPOSED PARTICIPATION

In this section we describe the scope of the proposed Bomem participation in NGST. The proposed contribution is the interferometer subsystem of an Imaging Fourier Transform Spectrometer (IFTS) for NGST.

Given the very broad wavelength range of NGST, it is believed that the subsystem will actually be composed of three separate interferometer modules and one dichroic module to steer the light into them. **This constitutes the baseline for the schedule and cost estimates presented in this report**.

The interferometer modules are complete subsystems capable of operating by themselves. The subsystem includes the opto-mechanical components (mirrors, beamsplitters and possibly collimating and condensing lenses or mirrors, depending on the primeship of these items) interferometer structural and thermal control assemblies, metrology assembly (metrology source, optics, detector and electronics) and interferometer control electronics. Figure 3 illustrates these components.

To make things clear and simple, this report focuses only on the IFTS interferometer subsystem. However there are a number of other subsystems or components that Bomem is interested in developing and for which Bomem possesses a unique, world-class expertise. Table 2 lists the three main areas where Bomem could contribute, along with rough-order-magnitude cost estimates. Bomem would be pleased to present the relevant capabilities and past experience and to hold discussions with CSA on these additional developments.

Table 2: Cost estimates for items not part of Baseline

Item	Number	Cost
Flight Calibration sources	3	REMOVED
Ground Segment - Data processing algorithms and software (level 1b)	1	REMOVED
Special test Equipment for instrument-level validation – Includes calibration sources and cryogenic collimator	1	REMOVED

3. DEVELOPMENT APPROACH FOR NGST IFTS

3.1 MODELS

Various approaches are possible for the development of space hardware as far as models are concerned. The model philosophy typically flows down from the risk analysis which can be done in a quantitative way, with targets set for the various models and to achieve an acceptable risk for the flight unit. Obviously, the mission criticality of the sensor, the overall mission (launch and platform) costs also fold in. We expect that the NGST expectations will be very high, typical of the larger science missions like EOS or ENVISAT. A for high probability of success is a must. This assessment implies that:

- Strict PA requirements will be enforced
- Rigorous development methods must be followed
- Reviews, control boards etc. will be implemented
- Risk reduction programs will be developed
- Mass models will be supplied
- Simulators will be used for verification throughout

We propose a development approach that uses basically three key models, 1) a breadboard which is currently under development, 2) an engineering model which will be form, fit and function compatible with the flight model but may use lower grade of space qualification on the electronics, and 3) a flight model.

To maintain reduced cost and accelerated development, the development approach will reuse available components as much as possible and make use of synergies with other space programs.

3.2 DEVELOPMENT CYCLES

3.2.1 Preliminary Design

The preliminary design phase is the first step in the project. It is concluded by the preliminary design review (PDR). At this review, there is an exhaustive review of all aspects of the system down to detailed subsystem concepts with all the required technical analysis to give confidence in the feasibility of the approach and its risk level. We present revised plans for the development, as well as plans for the manufacturing and testing of the various units. Action items are generated and the milestone is closed when these are resolved to the satisfaction of the customer. After closing, the manufacturing of the EM is released as well as long lead items for the FM as required. Finally, the results of risk reduction activities (breadboards and analysis) are presented.

3.2.2 Detailed Design

The detailed design phase pushes the design to the level where manufacturing can be started:

- The detailed drawings are produced
- The plans are turned into procedures
- The change control board is implemented
- Configuration control management is implemented

The phase is concluded after successful completion of the Critical Design Review (CDR) where the documentation is presented along with the EM test results. At this point, there must be great confidence in the probability of success of the instrument.

3.2.3 Manufacturing

Following the CDR, the manufacturing phase is started, first by the procurement of parts, their assembly into sub-assemblies and integration into the final sensor. As the work process, subsystem testing is performed, key and mandatory inspection points are met. The test readiness review (TRR) milestone is used to clear the way to final testing which will include the performance verification as well as the environmental qualification of the unit. Upon successful completion of the test plan, acceptance is granted by the customer and the unit is delivered.

3.3 TOOLS, TECHNIQUES AND METHODOLOGIES

Bomem uses several tools in the development process for its projects. They cover performance assessments, requirements flowdown and project management.

In the course its 25 years of experience in development Fourier Spectrometers, Bomem has gained a thorough understanding of the performance aspects of these instruments. Furthermore, we have integrated these tools in a formal software package for internal use and select customers. These allow:

- Rapid assessment of performance and performance drivers for FTS instruments including noise, accuracy and line shape aspects
- Simulation of the instrument to study the effect of various instrument parameters and abnormal operation. It also allows the creation of realistic data sets for training and verification of the ground segment software.

For more information on these tools, please refer to:

http://www.bomem.com/spectro/index.htm

We also intend to make use of a requirements flowdown tool called DOORS (Dynamic Object Oriented Requirements System see: http://www.qssinc.com/products/doors/introduction.html) for the systematic allocation of requirements to subsystems and generation of the various procedures and verification assessment.

Bomem uses for all its operations an integrated project management system that provides weekly information on the effort levels required and earned value status of all projects as well as new upcoming projects. This allows very accurate assessments of schedule and cost status for the program.

3.4 REVIEWS AND AUDITS

3.4.1 Formal Reviews

Reviews will be the formal tool to present a detailed insight of the actual status of the project. PA engineer shall ensure traceability of requirements through each phase during reviews. PA Engineer shall participate directly or with an inspection report to formal reviews. The following formal reviews shall be held at dates specified in the Development Schedule.

- Kick-off meeting
- Preliminary Design Review (PDR)
- Critical Design Review (CDR)
- Test readiness Review (TRR)
- Acceptance review

The scope of the various reviews is covered in section 3.2.

3.4.2 Peer Reviews and Audits

Peer reviews will be held regularly to provide an internal verification of the development activities within the group. Peer reviews will be led by the PA Engineer. The peer reviews shall provide a means for reducing the number of problems and enhance the performance of the product by mutual assistance. Peer reviews are expected throughout the project duration. Peer reviews will be held at contractor's place. The reviews will be pre-scheduled and material distributed in advance.

Audits shall be held when required. Initiated by the PA Engineer, they will be held in order to verify that the tools and techniques are in accordance to the requirements. Audit reports will be kept at the PA Engineers desk.

3.5 PRODUCT ASSURANCE ACTIVITIES

To ensure that the contractual requirements of the project are systematically achieved, deficiencies are detected, corrected and prevented from recurrence, a Product Assurance program will be implemented.

The following Quality Assurance activities shall be performed:

- participation in writing coherent development, analysis, production and test plans for QA related issues,
- participation in reviews, audits and meetings,
- ensuring adherence to standards and procedures,

- liaison with configuration management,
- involvement in problem reporting and resolution,
- validation and acceptance tests follow-up including non-conformance control.

Status list of QA activities will be maintained at the PA Engineer desk. It will be provided upon request for review.

3.5.1 Product Assurance Organisation

The contractor in charge of the NGST IFTS development should have Program Assurance activities in place. The organisation should be qualified to an external program as ISO9001. The PA organisation is under the responsibility of a Management Committee. The PA manager reports directly to the Project Manager and to this committee.

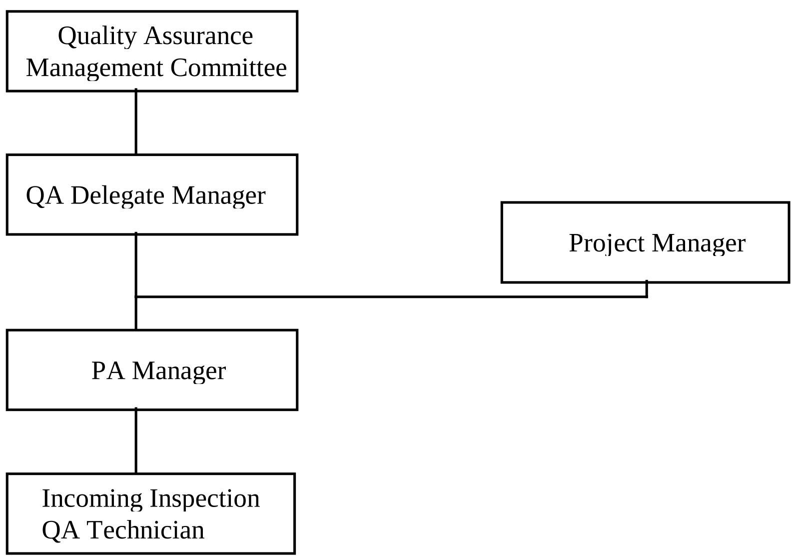

Figure 2: PA Organisation

The PA manager is responsible for implementation of the requirements in the project organisation and his contractors/suppliers.

Higher level contractors shall have right to access to PA activities as long as it is in respect with proprietary rights.

3.5.2 Review of documents

PA manager will participate in the review of documents and release cycle of specifications, plans, procedures and other documents related to the project. PA manager will review documents based on their conformance with quality assurance aspects.

This applies particularly to the Test Procedures.

3.5.3 Progress Reports

PA activities are reported in the monthly progress reports. These reports present problem areas and recommended solutions, if any. Non-conformance statuses are reported. PA documentation status is also reported.

3.5.4 Non-Conformance Reports

Non-conformance reports follow the procedure for Non-Conformance Control. When a non-conformance is detected, a non-conformance report is prepared on an in-house report. Non-Conformance Reports are presented in the monthly progress report.

3.5.5 Tests Witnessing

During testing, PA manager attends selected tests and/or attends testing activities to confirm that Test Procedures are followed correctly.

3.6 VERIFICATION STRATEGY

The verification strategy derives directly from the system and subsystem requirements through the establishment of the verification approach for each of the specific requirements. Specific approaches, in order of decreasing preference are:

1. By test. A direct measurement of the requirement to be met. The mass is measured on a scale.
2. By test and analysis. A direct measurement is not possible and some calculations are required to achieve the verification from system level measurements.
3. By analysis. A direct measurement is not possible and the compliance can only be determined from a model
4. By inspection. A simple visual inspection of a feature is required. Applies to markings, for example.
5. By design. When no other way of insuring that the requirement will be met is a design review. Applies to safety features and failure cases.

The verification strategy is determined early in the program for the system and similarly are defined for the subsystems as they get defined. They are reviewed at the major review to achieve a reasonable balance of cost and risk.

4. RISK ANALYSIS AND MITIGATION PLAN

4.1 METHODOLOGY

While there are many ways to assess the risk in the course of a project we favour the DSMC (Defense Systems Management College) approach that we used on several NOAA programs. A team surveys the project and determine the list of all risks including both technical and management risks. The consequences of problems in terms of costs and schedules are assessed independently and the some qualitative scores are combined for each of the identified components. It therefore becomes possible to sort the risk items in priority, assign targets levels as a function of time and finally put together a risk mitigation plan

The risk analysis can be performed as part of trade-off studies early in the design.

4.2 DESCRIPTION OF SUBSYSTEM

Figure 3 is a schematic illustration of the NGST IFTS interferometer subsystem. Clearly identified are the various components.

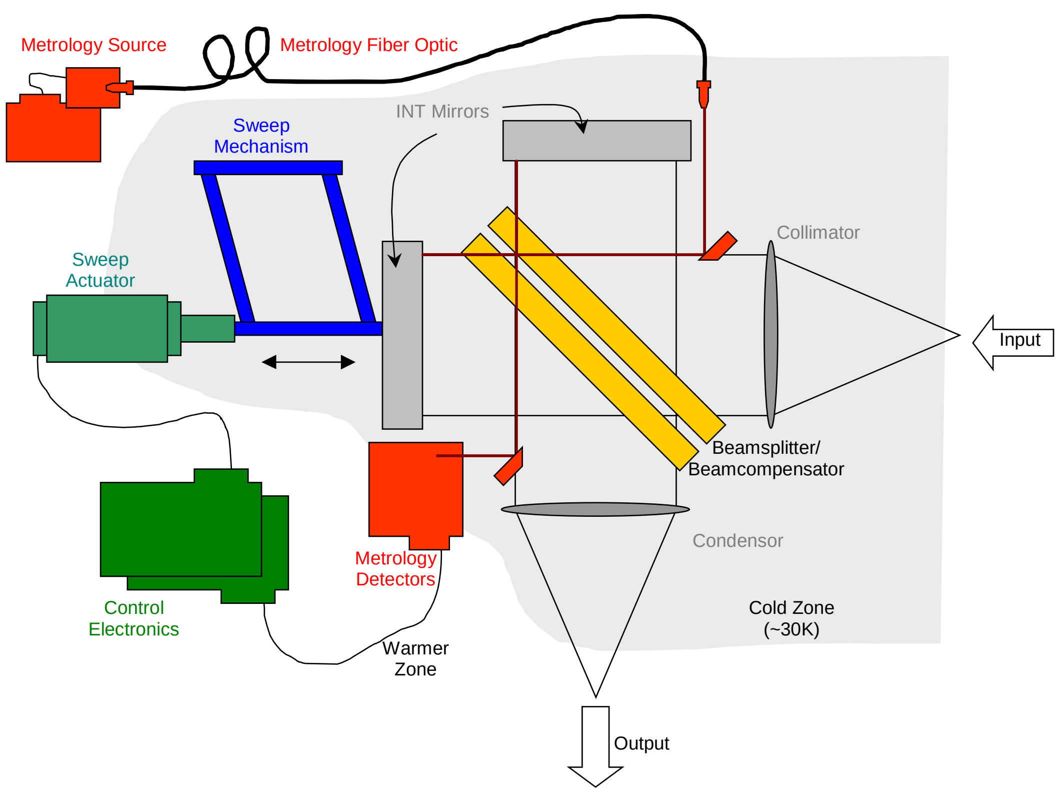

Figure 3 Schematic of NGST IFTS Components

4.3 LEVEL OF DIFFICULTY

As a complement to the formal risk analysis described above, Table 3 presents a first assessment of the risks associated with IFTS broken down against the key problem factors for a space-based cryogenic instrument. The rather low risk approach of the technologies involved with the interferometer doesn't require us to worry about the basic feasibility.

Table 3: Level of Difficulty matrix for the various interferometer components

Component \ Environment	Thermal	Radiation	Vibration	Lifetime
Collimator	Low	Low	Low	Low
Condensor	Low	Low	Low	Low
Beamsplitter / compensator	Medium	Low	Medium	Low
Interferometer Mirrors	Low	Low	Low	Low
Sweep Mechanism	Low	Low	Medium	High
Sweep Actuator	Hard	Low	Medium	High
Metrology Source	Medium	Medium	Low	High
Metrology Fibre Optic	Hard	Medium	Medium	High
Metrology Detectors	Medium	Medium	Low	Low
Control Electronics	Low	Medium	Low	Medium

4.3.1 Thermal Environment Considerations

We assume that the instrument is divided in a number of thermal zones. In Figure 3, we only show two zones, the coldest thought to be around 30 K, and another one labelled Warmer Zone. Some components will undoubtedly be located in the warmer environment. The main reason for placing a component in the warmer zone are is that 1) their function allows them to be located away from the cold optics such as electronic boards and 2) they generate heat. There is a high cost to place heat-dissipating components in the coldest environment. Current heat budgets supplied by NASA allow a few hundreds of mW to be dissipated by the interferometer subsystem in the 30 K area. For some components, it is not yet decided if they will be placed in the coldest zone or not. In this case they are illustrated in Figure 3 with the thermal zone border passing through them. One such example is the Sweep Actuator. From the point of view of the interferometric actuation, it would be ideal to have the actuator placed close to the sweep mechanism. However if an actuator with sufficiently low power dissipation cannot be found, a high dissipation device could be placed in the warmer area and transfer the mechanical motion using a stiff, insulating member, with possibly degraded actuation performance. The components for which the location is not yet known, a worst case in terms of risk is assumed, namely that they sit in the coldest zone.

Another example of component location to be determined is the Metrology Detectors. The detector themselves will lie in the coldest zone but the associated preamplifiers may be required to be very close to the detectors to minimise noise pickup. In this case low-power design and components will be required.

The Beamsplitter and Beamcompensator are made of visible light and infrared light transmitting elements. Many of these materials, especially in the infrared, are relatively soft or brittle, making their mounting much harder than, say monolithic metal mirrors. This is even more so in the case of cryogenic mounting and mounts appropriate for vibration (launch) environment. Both of these problems have been solved for a number of space instruments though. The level of difficulty score is thus considered medium.

The sweep mechanism would normally get a high to very high level of difficulty score, however in our baseline we assume the use of dynamic alignment that alleviates the problem of distortion of the thermal structure. On the down side, this choice complicates the metrology.

The Metrology Fibre Optic will be submitted to a high thermal gradient and this may place mechanical stresses that may change the light transmission characteristics but also that may produce mechanical failure.

The thermal environment imposes three types of constraints on components. The first one is the difficulty of operation in a very cold environment. The second difficulty is the testing of the devices in the cryogenic chambers and the increased complexity of such operations. The third constraint is the low-dissipation requirement, almost always associated with low temperature environments.

4.3.2 Radiation Environment Considerations

The radiation environment has very a low level of difficulty score for all mechanical components such as mirrors (the Collimator and Condensor are thought to be made of mirrors and not lenses) and the sweep mechanism. The transmission properties of materials used in transmission such as the Metrology Fibre Optic and Beamsplitter/recombiner may be affected by cosmic radiation. However we consider that only the Fibre Optic carries a certain level of difficulty because of the long optical path and the limited choices of fibre material. As it is the case for all space development, the electronic components potentially carry a high level of difficulty associated to space radiation but we assume that we can find a solution appropriate for the level of NGST cosmic radiation. This solution will be similar to that found for the rest of the NGST system.

4.3.3 Vibration Considerations

Most of the vibration considerations in space systems are usually centred around the initial launch perturbations. This is the case for the NGST IFTS, however a Fourier Transform spectrometer requires interferometric alignment requires tolerance to vibration during operation also. When an interferometer gets out of alignment, it efficiency, and consequently its sensitivity, degrades very rapidly.

The vibration environment and the thermal distortions are the factors most often cited by critics to say that the operation of a FTS in space is a risky business. This is true of FTS that *passively* rely on their structure to maintain alignment through the initial launch vibrations and through the structural deformations caused by spatial and temporal thermal gradients. The situation is different however if a FTS equipped with a *dynamically* aligned system is used.

The baseline Bomem NGST IFTS has a dynamic alignment subsystem which is shares components with the metrology. The dynamic alignment utilises the light from the metrology source and adds a number of detectors alongside the metrology detectors to sense the interferometric alignment. The dynamic alignment electronics sends a signal to a pair of short-stroke actuators (like single element piezo) to correct the alignment. This subsystem allows the system to readjust after a launch perturbation and allows to compensate thermal distortions. It allows us to design a much cheaper interferometer structure with traditional space materials, to save mass and greatly reduce the "interferometer in space" risk. It also generates significant saving during testing by having this sensing device built-in the interferometer subsystem, allowing to "see" what perturbations are experienced while the system is cooled down to 30 K. Cryogenic interferometer systems such as the CIRS on CASSINI is a good example of the problems encountered (see papers 04 and 24-26 of the SPIE Vol. 2814, Cryogenic Optical Systems and Instruments VII, Denver August 1996) during the testing of a passive system.

Bomem invented the dynamic alignment more than 25 year ago.

4.3.4 Lifetime Considerations

Lifetime in space issues affect 1) components with moving parts, 2) electronic components and 3) optical components in transmission. Lifetests will definitely be performed on the sweep mechanism, sweep actuator and dynamic alignment mechanism and actuators, all of which are moving parts.

The lifetime of electronic components in general is of concern, but the selection of space qualified electronic components is routinely performed for all space developments and does not carry excessive risk. Special attention is to be devoted to the metrology source which is thought to be a solid state laser diode at 1.55 μm. We plan to select a laser diode tested for another space program at Bomem (or elsewhere) or conduct lifetests in the lab during the development.

The darkening of optical components used in transmission because of radiation is a potential problem. The material will be selected form published space qualified lists to take care of this effect.

4.4 RISK ESTIMATE

The risk associated with the development of an interferometer subsystem for the NGST IFTS was analyzed using a standard method proposed by DSMC (Defense Systems Management College, www.dsmc.dsm.mil). The method was used on other Bomem/ITT projects as a relative risk assessment method. It analyze the probability of development failure by looking at 3 different causes of failure and evaluate the importance of three type of consequences in case of failure as defined in Table 4. By selecting the appropriate weighting factors between each item, one can evaluate an overall risk for a specific action. The formulae used to calculate the final risk factor Rf is given in Table 6. The table shall be used to compare each action item relative to another one to assess priority.

It is important to highlight the fact that this evaluation is performed on the risk of development process failure and not on the risk of failure of the instrument in flight. An example would be, that midway in the project the optical fiber selected cannot be space qualified for cryogenic space operation. The method evaluate the risk and consequence associated with such an event and the impact of a work around solution. It is therefore assumed that the instrument will work properly once in space.

Table 4: DSMC Probability & Consequence Definitions

Probability Definitions (Pf)			
Magnitude	**Maturity (Pm)**	**Complexity (Pc)**	**Dependency (Pd)**
0.1	Existing	Simple design	Independent of existing system, facility, or associated contractor
0.3	Minor redesign	Minor increases in complexity	Schedule dependent on existing system, facility, or associate contractor
0.5	Major change feasible	Moderate increase in complexity	Performance dependent on existing system performance, facility, or associated contractor
0.7	Technology available, complex design	Significant increase	Schedule dependent on new system schedule, facility, or associate contractor
0.9	State of art, some research complete	Extremely complex	Performance dependent on new system schedule, facility, or associate contractor

Table 5 DSMC Consequence Definitions

Consequence Definitions (Cf)			
Magnitude	**Technical (Ct)**	**Cost (Cc)**	**Schedule (Cs)**
0.1	Minimal or no consequences, unimportant	Budget estimate not exceeded, some transfer of money	Negligible impact on program, slight development schedule change compensated by available schedule slack
0.3	Small reduction in technical performance	Cost estimates exceed budget by 1 to 5 percent	Minor slip in schedule (less than 1 month), some adjustment in milestones required
0.5	Some reduction in technical performance	Cost estimates increased by 5 to 20 percent	Small slip in schedule
0.7	Significant degradation in technical performance	Cost estimates increased by 20 to 50 percent	Development schedule slip in excess of 3 months
0.9	Technical goal can not be achieved	Cost estimates increased in excess of 50 percent	Large schedule slip that affects segment milestones or has possible effect on system milestones

Table 6: DSMC Risk Factor Definition

	Risk Factor, $Rf = Pf + Cf - Pf \times Cf$
	Probability of failure, $Pf = a(Pm) + b(Pc) + c(Pd)$
	Consequece of failure, $Cf = d(Ct) + e(Cc) + f(Cs)$
Pm =	Probability of failure due to hardware maturity
Pc =	Probability of failure due to degree of complexity
Pd =	Probability of failure due to dependence on other items
Ct =	Technical consequences due to failure of selected technology (replacement options)
Cc =	Cost consequences due to failure of selected technology
Cs =	Schedule consequences due to failure of selected technology

The summary of the analysis for the development of an interferometer subsystem for the NGST IFTS is given in Table 7. The three most important risk elements are found to be: 1) the sweep actuator performance, 2) the control algorithms and software and 3) the metrology source qualification. Section 4.5 addresses the mitigation of these risks.

Table 7: NGST IFTS Risk Factor

Risk No.	Item \ Weighting Factors	Maturity (Pm) a 0.33	Complexity (Pc) b 0.34	Dependency (Pd) c 0.33	Probability of Occurrence (Pf) Pf = a Pm + b Pc + c Pd	Technical Factor (Ct) d 0.3	Cost Factor (Cc) e 0.15	Schedule Factor (Cs) f 0.55	Consequence (Cost of Occurrence) (Cf) Cf = d Ct + e Cc + f Cs	Total Risk (Rf) Rf = Pf + Cf - (Pf * Cf)
1	Metrology Source qualification	0.3	0.1	0.5	**0.30**	0.5	0.7	0.9	**0.75**	**0.825**
2	Cryogenic Metrology Fiber Optic Qualification	0.3	0.1	0.5	**0.30**	0.5	0.2	0.5	**0.46**	**0.617**
3	Metrology Detector qualification	0.1	0.3	0.2	**0.20**	0.5	0.3	0.5	**0.47**	**0.577**
4	Sweep actuator performance	0.8	0.5	0.5	**0.60**	0.7	0.5	0.9	**0.78**	**0.912**
5	Sweep Mechanism performance	0.5	0.5	0.3	**0.43**	0.7	0.2	0.3	**0.41**	**0.663**
6	Sweep technique performance (step scan)	0.9	0.7	0.3	**0.63**	0.5	0.3	0.5	**0.47**	**0.806**
7	Dynamic alignment performance	0.9	0.7	0.3	**0.63**	0.7	0.1	0.5	**0.50**	**0.817**
8	Dicroic system qualification	0.3	0.3	0.5	**0.37**	0.7	0.5	0.7	**0.67**	**0.791**
9	Interferometer beamsplitter qualification	0.3	0.1	0.5	**0.30**	0.7	0.4	0.3	**0.44**	**0.603**
10	Mirror qualification	0.1	0.1	0.5	**0.23**	0.5	0.3	0.3	**0.36**	**0.508**
11	input/output optics qualification	0.1	0.1	0.5	**0.23**	0.7	0.3	0.5	**0.53**	**0.639**
12	Control electronics qualification	0.3	0.5	0.5	**0.43**	0.7	0.5	0.5	**0.56**	**0.751**
13	Calibration source performance	0.9	0.8	0.3	**0.67**	0.3	0.5	0.5	**0.44**	**0.814**
14	Control software & algorithm performance	0.7	0.5	0.2	**0.47**	0.7	0.3	0.8	**0.70**	**0.837**

4.5 MITIGATION PLAN

Table 8 presents the result of the risk analysis and drafts a mitigation plan. A part of the mitigation plan is currently underway with the breadboard contract (pre-phase A activities). This will give Bomem the ability to validate some of the technology planned for the interferometer revealed to be problematic. In fact the breadboard tests will address some of the crucial aspects of risk # 4, 5, 6, 7, and 15 which include the two top risk elements. For items # 1, 3 and 10 to 13, space qualification has already been performed on similar components on previous space instruments. These items are present in the risk evaluation because the ones required for the NGST IFTS may differ from existing space-qualified versions. It is thought that the instrument design can be modified to accommodate space qualified components.

Table 8: NGST IFTS Risk Factor and Mitigation

No.	Level	Risk Identified	Risk Mitigation planned during phase A
1	**0.825**	**Metrology Source qualification**	Assess requalification of diodes from programs with less stringent PA requirements.
2	0.617	Cryogenic Metrology Fiber Optic Qualification	Perform transmission and polarization tests at cryo temperatures
3	0.577	Metrology Detector qualification	Assess requalification of diodes from programs with less stringent PA requirements.
4	**0.912**	**Sweep actuator performance**	Perform testing on current breadboard prior to instrument design and select alternate technologies if necessary
5	0.663	Sweep Mechanism performance	Study several designs and run test on current breadboard
6	0.806	Sweep technique performance (step scan)	Perform extended testing on breadboard version
7	0.817	Dynamic alignment performance	Perform alignment by iterative optimization techniques
8	0.791	Dicroic system qualification	Research past cryogenic programs for mirror performance
9	0.603	Interferometer beamsplitter qualification	Research past cryogenic programs for mirror performance
10	0.508	Mirror qualification	Research past cryogenic programs for mirror performance
12	0.639	input/output optics qualification	Research past cryogenic programs for mirror performance
13	0.751	Control electronics qualification	Select space qualified components
14	0.814	Calibration source performance	Perform extended study and simulation of various approaches
15	**0.837**	**Control software & algorithm performance**	Test uncompiled high level version on breadboard.

5. SCHEDULE

Figure 4 shows the NGST IFTS schedule (bottom - ID 20 and higher) along with the NGST milestones (top – ID 1-19). The task listed in Figure 4 are described in Section 6.1. The schedule was constructed around four milestones provided by CSA, the NGST IFTS Kickoff, FM PDR, FM CDR and delivery.

ID	Task Name	WBS	Duration	Start	Finish
1	**NGST IFTS Interferometer Development**		**2354 day**	**Jan 25 '9**	**Feb 1 '0**
2	**NGST Top level Milestones**		**2354 day**	**Jan 25 '9**	**Feb 1 '0**
3	NASA PMC	Mils	0 day	Jan 25 '9	Jan 25 '9
4	NASA PNAR	Mils	0 day	Mar 1 '0	Mar 1 '0
5	NASA NAR	Mils	0 day	Mar 4 '0	Mar 4 '0
6	NASA PDR	Mils	0 day	Dec 10 '0	Dec 10 '0
7	NASA CDR	Mils	0 day	Nov 10 '0	Nov 10 '0
8	NASA PER	Mils	0 day	Feb 3 '0	Feb 3 '0
9	NASA TRR	Mils	0 day	Feb 1 '0	Feb 1 '0
10	NASA PSR	Mils	0 day	Sep 11 '0	Sep 11 '0
11	NASA LRR	Mils	0 day	Mar 5 '0	Mar 5 '0
12	NASA LAUNCH	Mils	0 day	Feb 1 '0	Feb 1 '0
13	**NGST IFTS Milestones**		**915 day**	**Jul 30 '0**	**Jan 28 '0**
14	NGST IFTS Kick-Off	Mils	0 day	Jul 30 '0	Jul 30 '0
15	FM PDR	Mils	0 day	Sep 16 '0	Sep 16 '0
16	FM CDR	Mils	0 day	Oct 17 '0	Oct 17 '0
17	FM MRR	Mils	0 day	Dec 16 '0	Dec 16 '0
18	FM TRR	Mils	0 day	Jul 30 '0	Jul 30 '0
19	FM Delivery	Mils	0 day	Jan 28 '0	Jan 28 '0
20	**NGST IFTS Management & Control**		**936 day**	**Jun 29 '0**	**Jan 28 '0**
21	Management	01	936 day	Jun 29 '0	Jan 28 '0
22	Formal Meetings	02	915 day	Jul 30 '0	Jan 28 '0
23	Cost & Schedule control	03	915 day	Jul 30 '0	Jan 28 '0
24	Product Assurance	05	915 day	Jul 30 '0	Jan 28 '0
25	Verification	06	915 day	Jul 30 '0	Jan 28 '0
26	**NGST IFTS System Engineering**		**693 day**	**Jul 30 '0**	**Mar 24 '0**
27	System Requirements	210	172 day	Jul 30 '0	Mar 26 '0
28	System Engineering	220	316 day	Jul 30 '0	Oct 14 '0
29	Performance Modeling	230	375 day	Aug 27 '0	Jan 31 '0
30	Lifetime Studies	240	490 day	Dec 11 '0	Oct 27 '0
31	Data Analysis S/W	250	275 day	Mar 27 '0	Apr 15 '0
32	Tests Facilities	260	397 day	Sep 17 '0	Mar 24 '0
33	System Test Requirements	290	120 day	Apr 2 '0	Sep 16 '0
34	**NGST IFTS Engineering Model**		**455 day**	**Aug 27 '0**	**May 23 '0**
35	EM Preliminary Design	310	100 day	Aug 27 '0	Jan 11 '0
36	EM Detailed Design	320	130 day	Jan 14 '0	Jul 12 '0
37	EM Manufacturing	330	175 day	Jul 15 '0	Mar 14 '0
38	EM Validation	340	45 day	Mar 17 '0	May 16 '0
39	EM Delivery	350	5 day	May 19 '0	May 23 '0
40	EM EIDP	359	20 day	Apr 28 '0	May 23 '0
41	**NGST IFTS Flight Model**		**743 day**	**Mar 27 '0**	**Jan 28 '0**
42	FM Preliminary Design	410	125 day	Mar 27 '0	Sep 17 '0
43	FM Detailed Design	420	281 day	Sep 20 '0	Oct 17 '0
44	FM Manufacturing	430	225 day	Oct 20 '0	Aug 27 '0
45	FM Validation	440	100 day	Aug 30 '0	Jan 14 '0
46	FM Delivery	450	10 day	Jan 17 '0	Jan 28 '0
47	FM EIDP	459	30 day	Dec 20 '0	Jan 28 '0

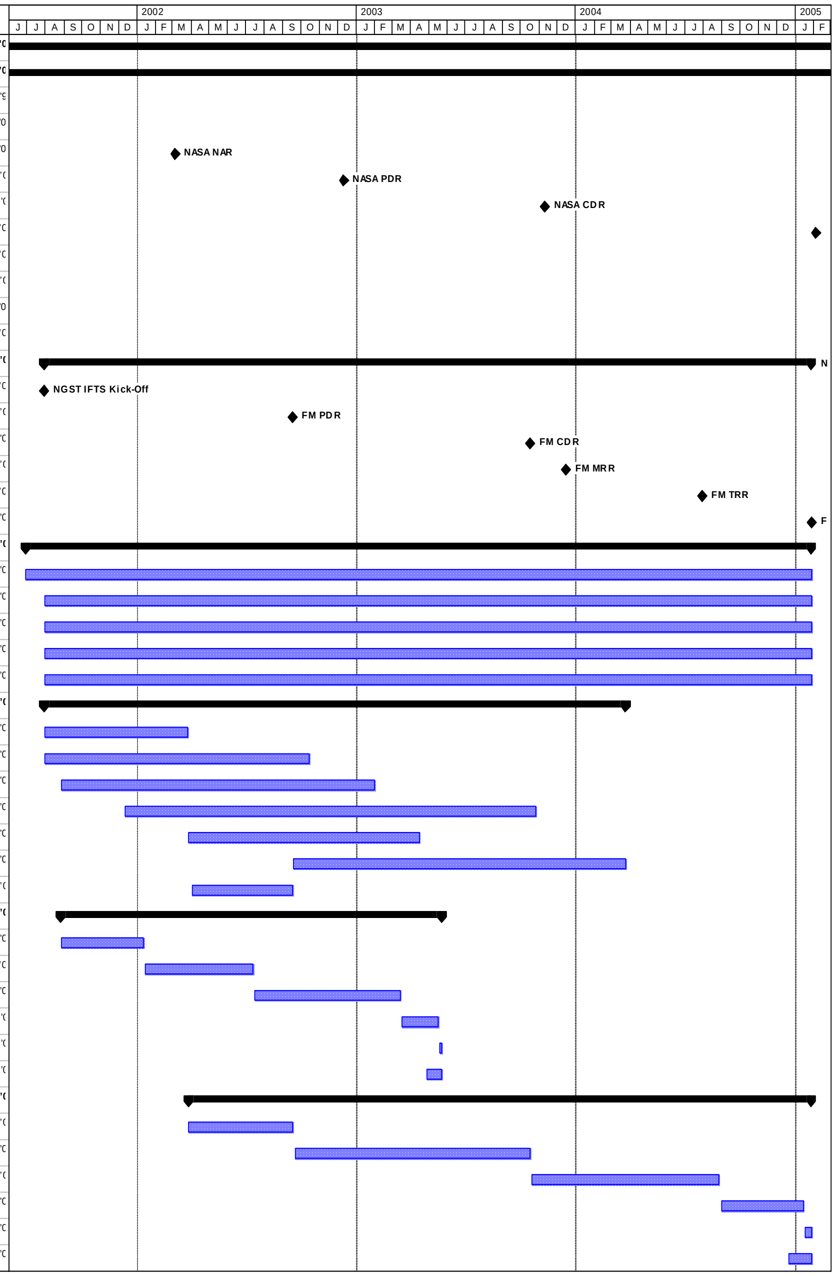

Figure 4 NGST IFTS Schedule

The resulting schedule is quite aggressive and is thought to increase the risk of the development. There is only a four month period between the kickoff and PDR of the EM. This is especially short considering that during that time a large team (>25) has to be built. The work performed on the breadboard (pre-phase A) will help quickly come to a technological baseline for the EM, but the proposed schedule is thought to be restrictive, Bomem would recommend to increase the timeframe by 20-40% if it is possible, by example starting the EM program earlier, perhaps at a reduced effort.

Bomem has the required expertise, size and is growing at a rate compatible with the staffing requirement of NGST. The SPIR division of Bomem is the world largest development team of Fourier Transform spectrometers.

6. BUDGET ANALYSIS

6.1 METHODOLOGY

The cost estimate was built using a bottom-up methodology. The work breakdown was first constructed using the models and development cycles described in Sections 3.1 and 3.2. The resulting work breakdown structure is shown in Figure 5. The work is divided in four classes of tasks. The 00X tasks pertain to project control and quality assurance. The 2XX tasks pertain to system engineering. The 3XX tasks pertain the to engineering model development and the 4XX tasks pertain to the flight model development.

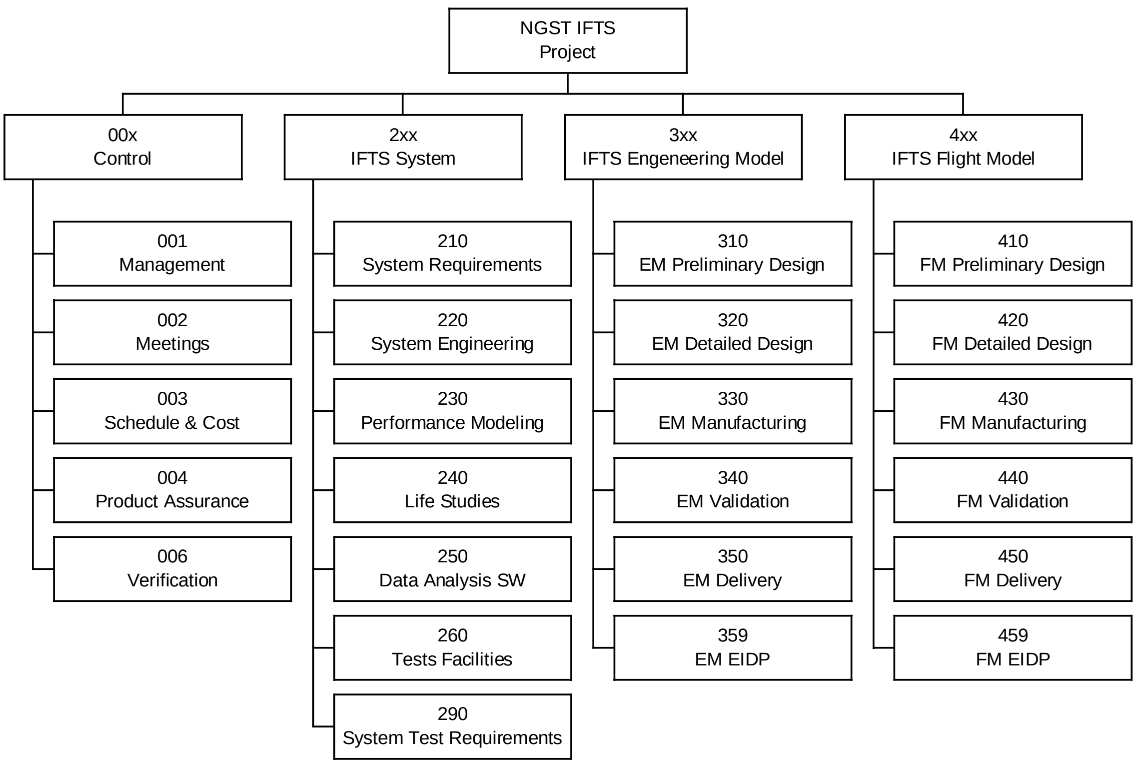

Figure 5 Work breakdown structure

Next a detail work form (Bomem F240 form) was filled out for every task (also known as WBS). Table 9 shows an example of the detail work form for WBS310 – EM preliminary design. The work in the WBS is broken down in easily identifiable subtasks requiring no more than a few weeks. This level of detail is sufficient to produce a realistic and solid cost estimate. The hours and material, contract, travel costs are wrapped up in a single summary page (see Table 10).

The level of efforts are entered based on experience on similar projects and based on the work already completed (See RD 2 and RD 3) and the risk analysis described in Section 4. The complete workbook (Excel) can be provided upon request.

Table 9: Example of a WBS detail work form. The I3S, I2S, T3S and T1S refer to labor categories and the entries are hours.

Task Title: *[NGST IFTS EM] Preliminary Design*
Task Objective: *EM Preliminary Design*

Start Date: August 27, 2001
End Date: January 11, 2002

Responsable

Description	I3S	I2S		T3S	T1S					MAT	CONT	VOY	Aut
Establish interferometer req. From instrument req.	150												
Sensor req. Draft	150	150											
Flowdown req. To subsystem	75	75											
Flowdown req. To ass'y	75	75											
NGST IFTS Interferometer General Concept	60	60											
NGST IFTS Interferometer Radiometric Concept/Analysis	60												
NGST IFTS Interferometer Optical Concept	150	150		150									
NGST IFTS Interferometer Mechanical Concept	225	300		450	450								
NGST IFTS Interferometer Electrical Concept	300	300		300									
NGST IFTS Interferometer Interface Concept	150												
NGST IFTS Interferometer Alignment Concept	150												
Alignment and Test Bench Concept	50			150									
NGST IFTS Interferometer Optical Performance Analysis	225												
NGST-P Instrument Radiance Analysis	150	100											
NGST IFTS Interferometer Prelim. Thermal Analysis	150	100											
NGST Interferometer preliminary structural analysis	150	100											
Mass & Power & Heat diss. budget first eval.	200	150											
Temperature Control System Design	160												
NGST IFTS Interferometer prelim. procurement specification	100												
Component and Material Evaluation	300												
Prelim Electronic Schematics				225	225								
Sweep Control algorithms	200	300											
PDR Engineering Documentation and Data List	150	300		150	150								
Total	**3380**	**2160**	**0**	**1425**	**825**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

6.2 COST DRIVERS

Several aspects of the development of the NGST IFTS have a significant impact on the overall cost.

6.2.1 Schedule

As discussed in Section 5 the schedule is thought to be very short and forces us to form a large NGST IFTS team which would not be as efficient as a smaller team. Increased communication between the team members will be required, because each member will be assigned to smaller, more specific tasks, limiting their view of the system-level requirements. This risk will be mitigated by the use of requirement control tools such as DOORS (see Section 3.3).

6.2.2 Testing

The testing of the NGST IFTS is a substantial effort because of the cleanliness requirement and more importantly because of the *cryogenic operation temperature*. Bomem has designed, built and tested two cryogenic interferometers in the past, but these where limited to liquid nitrogen temperatures (77 K). For the NGST IFTS, we are required to perform the testing in a chamber fitted with liquid nitrogen *and liquid helium* cooling equipment to reach the 30 K operation temperature. This type of test facility is significantly more difficult to design, built and operate. Cooling times are longer and operation costs (cryogens) are higher.

6.2.3 Temperature

The cost of design of the NGST IFT is significantly increased compared to standard earth orbiting Fourier Transform spectrometers because of its operating temperature. Significant thermal modeling and design will need to be performed. Although the thermal variations are thought to be smaller than for standard earth orbiting platforms, the absolute temperature is very low (30 K) requiring a significant effort spent on thermal management. In particular ultra-low dissipation devices will need to be used in the 30 K temperature environment.

6.2.4 Interfacing

Since the proposed Bomem contribution is the interferometer *subsystem* to the instrument, itself which is one *system* of the instrument suite (named the NGST ISIM – integrated science instrument module), itself which must comply with the platform interfaces, it is expected that the interface issues and the interface requirement flowdown process will drive a significant portion of the design effort.

6.2.5 Radiation, vibration, contamination

Finally the NGST IFTS development is significantly impacted by issues of radiation hardening, ruggedization against vibration and contamination control, all of which are standard development efforts for space hardware.

6.3 BUDGET ESTIMATE

Table 10 shows the summary of the cost estimate for the development of the interferometer module for the NGST IFTS, as described in Section 2. Table 11 provides the breakdown by task category. Table 12 provides the cost breakdown by WBS.

Table 10: Cost estimate summary

TABLE REMOVED

Table 11: Cost breakdown by task category

TABLE REMOVED

Table 12: Cost breakdown by WBS

TABLE REMOVED

7. REFERENCE MISSIONS

7.1 MIPAS, AIRS, IASI AND TES

The above thee missions are current on-going programs in which Bomem is involved and where similar technologies to IFTS are used. They include ESA, EUMETSAT/CNES and NASA/EOS programs. The cost for the development and production of the first flight unit is remarkably similar, in the vicinity of INFORMATION RELATIVE TO COST REMOVED. This includes the cost of the detectors, which represents typically 20-25% of the cost. These instruments are representative of the IFTS as being key instruments on a world class satellite program. They are however burdened by large industrial teams, frequent replanning (as NGST could be) and led by prime contractors with little initial experience in this type of instrumentation. INFORMATION RELATIVE TO COST REMOVED

7.2 CRIS

The Cross-track IR sounder (NPOESS) is the next generation low earth orbit IR sounder for operational meteorology. Bomem is part of the ITT team and is in charge of the interferometer, the calibration hardware and algorithms. This work is in a competitive Phase A and after a down-selection process, we expect an award for multiple units. This opportunity is an important long-term prospect for space-borne interferometers. Very aggressive cost targets are provided given the long-term nature of these weather programs and the relative simplicity of the instrumentation. INFORMATION RELATIVE TO COST REMOVED.

7.3 ACE

Bomem, ITT and NASA Langley are collaborating on FTS design in the ACE (Atmospheric Chemistry Experiment) program. This instrument is proposed for the Canadian SciSAT-1 mission to be flown in 2001. The instrument concepts derives directly from the Langley WEB interferometer with its highly efficient folded optical path and moving cube corners. An ACE prototype has been put together by the team during the summer of 1998 and can serve as the basis for further prototyping. The instrument will also make use of miniature frequency stable lasers.

INFORMATION RELATIVE TO COST REMOVED

7.4 SUMMARY

While this type of analysis can only provide a rough assessment of cost credibility, we see that the IFTS costs should lie in the INFORMATION RELATIVE TO COST REMOVED bracket (including detector), excluding ground-processing hardware or software.

8. ABBREVIATIONS AND ACRONYMS

CDR	Critical Design Review
CIF	Change Implementation Form
CIRS	Composite Infrared Spectrometer
DOORS	Dynamic Object Oriented Requirements
DSMC	Defense Systems Management College
EM	Engineering Model
ESA	European Space Agency
FM	Flight Model
H/W	Hardware
IFTS	Imaging Fourier Transform Spectrometer
ISIM	Integrated Science Instrument Module
IT	Integration Test
NGST	Next Generation Space Telescope
PA	Product Assurance
PDR	Preliminary Design Review
QA	Quality Assurance
QM	Qualification Model
RD	Reference Document
S/W	Software
TPR	Test Procedures & Reports
TRR	Test Readiness Review
WBS	Work breakdown Structure

— End of document —