TECHNICAL ASPECTS OF TECHNOLOGY TRANSFER DURING THE LORAL FAILURE INVESTIGATION

Background

The February 14, 1996 failure of the PRC Long March 3B during the launching of the Intelsat 708 communications satellite, built by Loral, set in motion a number of accident investigation and reporting activities. These brought PRC engineers and designers face-to-face with Western engineers and technical experts in satellite and related rocket technologies.

The initial technical analyses of the accident were conducted by two groups of PRC scientists and engineers. These analyses were presented in several sessions in March, April, and May 1996 to representatives of the satellite launch insurers, re-insurers, Intelsat and Loral.

Initially, greater priority seems to have been placed on briefings and discussions with representatives of Hughes and the PRC-controlled Asia Pacific Telecommunications Co., Ltd., and their respective insurers and re-insurers. This was because Hughes was the builder and Asia Pacific Telecommunications was the owner of the Apstar 1A satellite, which was the next satellite scheduled to be launched (on April 1) on a Long March rocket (albeit the Long March 3, a different version from the 3B). Before that scheduled next launch could take place, these organizations would need to be convinced that the Apstar 1A would not be exposed to the same defects or hazards as those in the Long March 3B rocket that had caused the failure of the Intelsat 708 launch.

Loral, too, was highly motivated to remedy the defects in the Long March 3B because its upcoming Mabuhay satellite launch was the next scheduled aboard the Long March 3B.

On March 9, 1996, Hughes representatives toured the launch site facilities, which had suffered some damage as a result of the Intelsat 708 accident, and subsequently held discussions concerning the findings of the PRC accident investigations.

On March 14, 1996, a meeting was held with the insurance underwriters for the Apstar 1A in Beijing. Hughes and Asia Pacific Telecommunications representatives were also in attendance. The main information the PRC rocket authorities and the APT representatives sought to convey to the insurance underwriters was that the accident investigation of the Intelsat 708 launch failure had shown that the Long March accident was caused by the failure of the inertial measurement unit. This is the subsystem that provides attitude, velocity, and position measurements for guidance and control of the rocket.

The PRC representatives stated that the inertial measurement unit used on the Long March 3B that failed was different from the one used on the Long March 3, which was the rocket that would be used to launch the Apstar 1A, and that therefore there should be no cause for concern for the launch of the Apstar 1A.

Representatives of the insurance underwriters then stated that insurance of the Apstar 1A launch would be conditioned on delivery of a final report on the root causes of the Long March 3B failure, and a review of that report by an independent oversight team.

A subsequent meeting with the insurers and re-insurers was scheduled to take place in Beijing around mid-April, at which time the PRC representatives were to present in detail the results of their accident investigation of the Long March 3B.

The Apstar 1A re-insurers meeting took place on April 15 and 16. It included both items normally addressed in preflight reviews as related to the upcoming Apstar 1A launch, and the issues arising from the Long March 3B rocket failure in the Intelsat 708 launch.

The latter issues were largely covered in presentations by Huang Zuoyi, President of Great Wall Aerospace, a California-based subsidiary of China Great Wall Industry Corporation. These presentations substantially made the same points as were made at the March 14 meeting: the Long March 3B failure was in the inertial measurement unit, and this was not cause for concern for the Apstar 1A launch since it would be launched by a Long March 3 rocket having a different (and older) inertial measurement unit with a previous record of successful launches.

At this same meeting, in response to the re-insurers' earlier-stated requirement, China Great Wall Industry Corporation announced the creation of an Independent Review Committee to review the findings and recommendations of the PRC committees investigating the Long March 3B failure.

Dr. Wah Lim of Loral was to be the Independent Review Committee Chairman, and Nick Yen, also of Loral, was to be the Secretary. Both were present at the meeting and discussed the role of the Independent Review Committee, and the roster of members of the committee. The two prospective members from Hughes, Dr. John Smay and Robert Steinhauer, were also present, as was Nabeeh Totah, a senior technical staff member at Loral, who would serve as one of four technical experts provided by Loral to support the Independent Review Committee.

During this meeting, the participants were taken on a tour of the Long March rocket assembly area and were shown, in partially-opened state, units described by the PRC as the older Long March 3 inertial measurement unit and the newer Long March 3B inertial measurement unit. Thus, almost half of the Independent Review Committee participants (members plus supporting experts) had prior exposure to the findings and views of the PRC representatives derived from their accident investigations, and they had opportunities to raise questions and issues with the PRC representatives well before the first meeting of the Independent Review Committee.

The Long March Series of Rockets

The PRC Long March rocket evolved from the PLA's long-range ballistic missiles, much as most of the U.S. heavy-lift rockets were derived from earlier ballistic missiles: the Atlas E and F; the Titan II; and the Thor (the forerunner of the Delta rocket).

Much of the civil and commercial satellite traffic needs to be put into geosynchronous orbit over the equator at 22,000 miles above the Earth's surface. At this altitude, the satellite orbital speed is exactly that needed to keep a constant position over a point on the surface of the rotating earth below. A common method of achieving these orbits is for the rocket to first place the satellite into a highly elliptical geosynchronous transfer orbit, and then for the satellite itself to circularize the orbit at geosynchronous altitude, using a so-called kick rocket motor on board the satellite.

The need to achieve geosynchronous transfer orbit with increasingly heavy payloads has led rocket designers to add high-energy liquid oxygen/liquid hydrogen upper stages on top of the original lower stages that still use the fuels and oxidizers of their ballistic missile antecedents. In addition, increased thrust levels have been added to these first stages by means of strap-on booster rocket motors. The Long March series of rockets has gone through just this set of evolutionary steps, paralleling in this respect its American counterparts.

Guidance Systems for Ballistic Missiles and Rockets

The requirements for guidance accuracy for intercontinental ballistic missiles depend on a nation's strategic objectives and policies, but they are generally more demanding than the accuracy that is required to place a satellite into geosynchronous transfer orbit. For example, for a ballistic missile with a target range of 5,500 miles, an error of one foot per second in the velocity at last-stage burnout (23,000 feet per second) would lead to an error in target impact of about one mile. A satellite on orbit, on the other hand — if such accuracy in its orbital parameters is required — can measure its position over an extended period of time with the aid of ground tracking, and adjust for orbital velocity differences of this magnitude with on-board thrusters using only a few pounds of fuel.

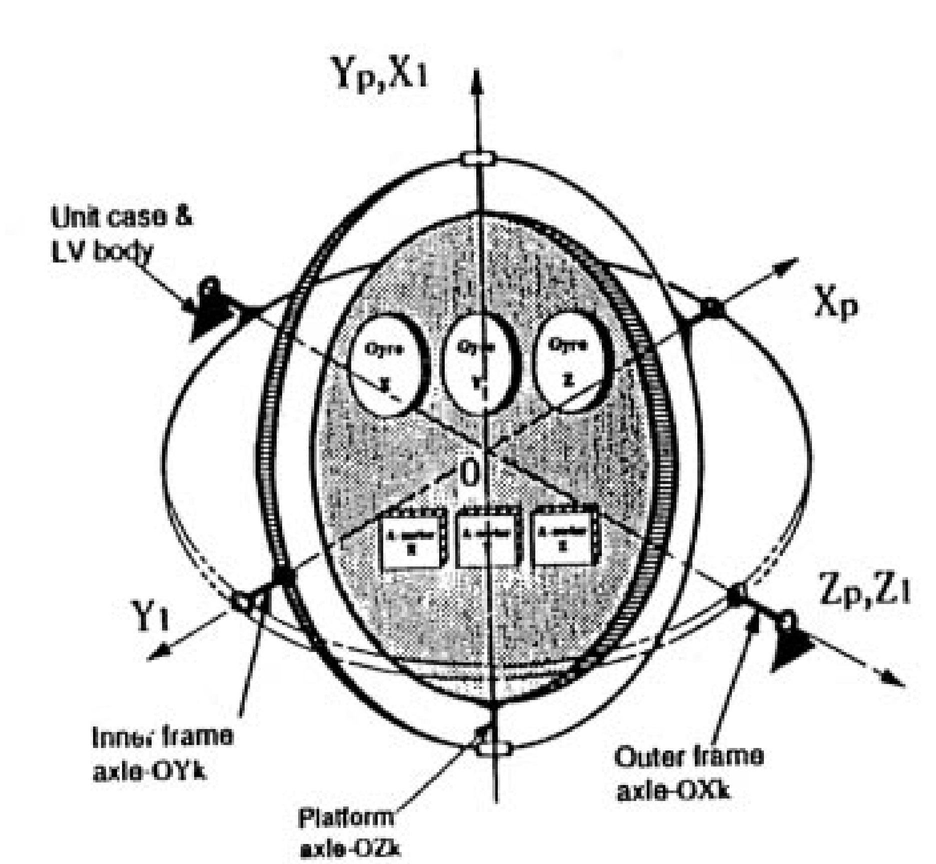
It appears that in the PRC, guidance systems for rockets were initially based on instruments and inertial platform technologies taken over from the predecessor ballistic missile programs. But the PRC's development of inertial guidance for rockets has, as in the West, developed over time in directions somewhat different than inertial guidance for intercontinental ballistic missiles.

Over time, inertial guidance systems for rockets have incorporated simpler, cheaper, lighter, and more reliable components, as well as concepts such as ring-laser gyros and strapdown technology in which there is no inertial platform required to maintain a fixed position in space. In contrast, the latest U.S. ICBM inertial guidance system is the Advanced Inertial Reference Sphere (AIRS), used on the Peacekeeper missile. It is probably the most accurate inertial measurement unit ever developed and manufactured. The inertial measurement units used on earlier ballistic missiles used an inertial platform mounted on a set of gimbaled axis frames. The AIRS, on the other hand, consists of a beryllium sphere floating in a fluorocarbon fluid within an outer shell, with no gimbals or bearings at all, housing highly accurate gyros and accelerometers. The AIRS is complex, difficult to manufacture, and very expensive.

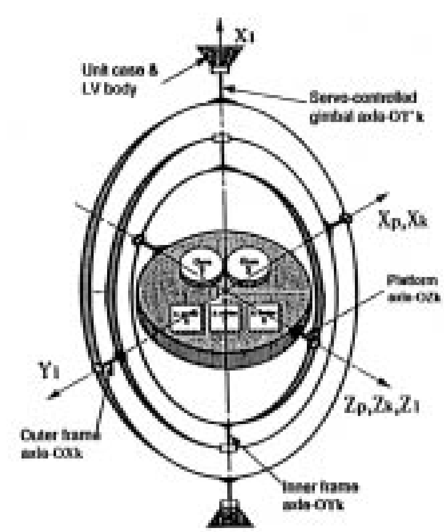
The PRC representatives had indicated (or allowed the impression to be conveyed) to their Western customers and their insurers that the inertial measurement unit used on the several versions of the Long March 2 and 3, up to the 3B, was essentially identical to the inertial measurement unit used on their long-range ballistic missile. Rather than basing their claims of the inertial measurement unit's reliability on the more slender record of space launches alone at the time the Long March was first offered to foreign customers for launch services, the PRC may have offered this information to enhance the record of reliability of the inertial measurement unit. This permitted the PRC to show that the Long March had a longer and larger record of successful flights than would be assumed on the basis of its use in space launches only.

As presented by the PRC participants, the older inertial measurement unit used in the Long March 3 weighed 140 kilograms, and measured 500 x 600 x 800 mm. It had three gimbal axes and three single-axis gyroscopes on its inertial platform. It was also said to have a high degree of redundancy to preclude single point failures. The newer Long March 3B inertial measurement unit was presented as having a weight of 48 kilograms, and dimensions of 300 x 300 x 400 mm. It had four gimbal axes with only two (two-axis) gyroscopes on its inertial platform.

The fourth gimbal axis in the newer Long March 3B unit is associated with the addition of a follow-up frame to the platform mechanism. The follow-up frame precludes the occurrence of gimbal lock. This can take place in inertial platform assem-



IMU of LM-3



IMU of LM-3A/3B/3C

An artist's rendition of the difference in design between the inertial measurement unit used on the Long March 3 as compared to that used on the Long March 3A, 3B, and 3C rockets. The two illustrations are not shown to the same scale; the Long March 3 inertial measurement unit is much larger, and weighs nearly three times more.

blies when the rocket undergoes large angles of inclination, and two of the frames of a three-gimbal inertial platform mechanism move into the same plane.

Thus, the Long March 3B inertial measurement unit, as described and displayed by the PRC participants, is an essentially different subsystem from the inertial measurement unit of the Long March 3. In fact, it was reported that some members of the insurance community felt that the PRC had an obligation to inform them of this change affecting the reliability and performance of the Long March series of rockets, and should have done so before the Intelsat 708 launch.

The Meetings of the Independent Review Committee

The first meeting of the Independent Review Committee was held in Palo Alto, California, on April 21 and 22, 1996. Some members of the committee and its supporting experts had already had considerable prior exposure to the facts of the accident that occurred during the flight of the Long March 3B rocket carrying the Intelsat 708 satellite.

According to its charter, the Independent Review Committee was nominally an entity responsive to the China Aerospace Corporation, the parent company of China Great Wall Industry Corporation. The President of China Aerospace Corporation convened the Independent Review Committee. It was he who appointed the Independent Review Committee's Chairman, Dr. Wah Lim of Loral.

During the first day of the first Independent Review Committee meeting, those committee members present were briefed by a Loral export control officer concerning export control limitations that would apply to Independent Review Committee activities. In the recollection of several of those present, there were few questions and little discussion of the briefing — a surprising situation, in view of the seeming dissonance between the Independent Review Committee charge in its charter and the restrictions expressed in the export control briefing.

In that briefing, members of the Independent Review Committee were told that disclosure of information that would enhance rocket or missile capabilities of the PRC would not be permissible. But as one participant in the Independent

Review Committee activity said, "You can't help but get a little bit too detailed in the interest of finding out what the cause of the failure is. It's possible there could have been [circumstances] where you ask leading questions which you're not supposed to."

The first meeting was devoted to familiarizing the members of the Independent Review Committee, especially those who had not taken part in the earlier April 15 and 16 meeting, with the circumstances of the Long March 3B failure, the data acquired from telemetry, and the findings of the PRC accident investigation up to that time. The Independent Review Committee asked many questions having to do with understanding and interpreting the following:

- **Telemetry data**
- **The particulars of the inertial measurement unit hardware**
- **The details of the Long March 3B pre-launch procedures and launch operations**
- **The vibration and acoustic environment to which the inertial measurement unit was exposed in flight and in ground testing**
- **The scope and technical details of the analyses pursued in the PRC accident investigation**

Many of the Independent Review Committee's questions could not be answered immediately, and were listed for consideration at the second meeting of the committee that was to be held in Beijing on April 30 and May 1, 1996.

The PRC presentations at the Independent Review Committee meeting on April 21 and 22 repeated the main accident investigation finding reported in the meeting of April 15 and 16: that the cause of the failure was in the inertial measurement unit. Further, the failure in the inertial measurement unit was ascribed by the PRC participants to the loss of current to the torque motor of the *inner* frame gimbal axis. This loss of current, in turn, was hypothesized to be due to a break in the wire (or soldered joint) that supplied power to the torque motor.

In support of this hypothesis, the PRC participants presented "hardware in the loop" simulation results. The simulation showed agreement with telemetered inertial platform data from the failed flight for about the first six seconds after liftoff. On this basis, the Independent Review Committee granted in its statements and reports to the PRC that the loss of current to the *inner* frame gimbal torque motor was the most probable cause of the failure.

However, the telemetered flight data indicated three cycles of reversals of platform motion over the approximately twenty-two seconds of flight from liftoff to impact. These data were not matched by the simulations. To explain this cyclic motion, the PRC representatives assumed that the break in the circuit to the *inner* frame axis torque motor was such that electrical contact could be successively made and broken three times during the flight.

From the first time this explanation was offered, the members of the Independent Review Committee were skeptical of it, and repeatedly questioned it. The PRC participants, on the other hand, never abandoned it from the beginning to the end of the Independent Review Committee activity.

The Independent Review Committee's refusal to accept the adequacy of the PRC participants' explanations, analyses, and simulations to determine the root cause of the failure, and the committee's insistence on the need to simulate the periodic platform motions for the entire 22 seconds of flight, are the main issues raised in the minutes of its first meeting. These topics remained as prominent issues in the committee's preliminary report.

Because the U.S. Government directed cessation of its activities earlier than planned, the preliminary report was the last report issued by the Independent Review Committee.

The other significant issues that were given serious attention by the Independent Review Committee at its first meeting, as reflected in the minutes of the meeting, included the list of questions that the PRC participants were to answer at the following meeting to be held in Beijing. These questions concerned the following areas:

- **Quality assurance and control,** including acceptance testing procedures for the inertial measurement unit

- **The design and manufacture of inertial measurement units,** and their assembly into the rockets
- **The validity of the test environments** (vibration, noise, and thermal) in the Long March 3B vehicle equipment bay where the inertial measurement unit was located
- **Range safety at the launch site**

The second meeting of the Independent Review Committee took place in Beijing on April 30 and May 1, 1996. On the major issue of the cause of the Long March 3B failure during in the launch of the Intelsat 708 satellite, the PRC participants' conclusions remained unchanged.

The most probable root cause of the accident, the PRC asserted, was a break in the circuit carrying current to the torque motor of the *inner* frame gimbal. This break they attributed to a failure in the wire directly connected to the torque motor, or one of its soldered joints.

T**o explain the three cycles of platform motion observed in telemetry, the PRC still advanced the hypothesis** that the motion of the wire and the platform caused electrical contact to be made and broken three times. In the failure-tree analysis presented by the PRC participants to examine all possible causes of the Long March 3B launch failure, all failure possibilities not involving the torque motor of the *inner* frame gimbal axis were ruled out.

The PRC participants also presented a list of proposed fixes to the Long March 3B inertial measurement unit. This list included:

- **Improvements in soldering**
- **The cutting of wires** to allow length sufficient to allow for the maximum platform frame travel to be encountered
- **Non-destructive pull tests of soldered joints**
- **X-ray inspection of wires**
- **Improved acceptance testing, and addition of acoustic environment**

- **Redundancy in design**
- **Greater attention to quality supervision of suppliers**

Most of these items follow from the erroneously postulated broken-wire failure mode.

However, the PRC's proposed improvements in acceptance testing, with the addition of an acoustic environment, are of more general application — they could apply no matter where in the inertial measurement unit the failure might have occurred. Most of these corrective measures relate to some extent to questions raised by the Independent Review Committee at its first meeting.

Technical Information and Advice Transferred in Independent Review Committee Meetings and Reports

It is not possible to consider all of the technical information and advice that may have been imparted to the PRC representatives during the period of Independent Review Committee activity, since verbatim records of the meetings were not kept at either of the main meetings or at any of the meetings of subgroups (including "splinter groups" involving Independent Review Committee members, staff, and PRC personnel, and meetings involving only Independent Review Committee members and staff) that were held. Therefore, this assessment is based on the Select Committee's review of available records of the Independent Review Committee meetings, its communications with Independent Review Committee members mainly relating to composing and reviewing reports, and its interviews with individual participants in the Independent Review Committee's activities more than two years after that committee had ceased its activities.

Moreover, the perspective adopted in this assessment is that of viewing all of the information as a whole, in the context of the Long March 3B failure and PRC actions not only to find and correct the failure, but also to convince customers, insurers, and re-insurers that the causes of the failure had, in fact, been found and corrected.

From a technology transfer standpoint, it is noteworthy that the Independent Review Committee charter called on the committee not only " . . . to perform an independent assessment of the most probable cause or causes of failure," but also to ". . .

review the corrective action plans proposed by the [PRC's Failure Investigation Committee] and make its assessments and recommendations to [China Aerospace Corporation] and [China Great Wall Industry Corporation]." [Emphasis added]

Clearly, the charge to the Independent Review Committee went beyond making judgments about whether or not the PRC had convincingly determined the cause of failure. The Independent Review Committee members were not only to go beyond reviewing the PRC failure analysis to making *an independent assessment of the most probable cause or causes of failure,* they were also to review and make *assessments and recommendations concerning the corrective measures to remove the causes of failure.*

Taken literally, corrective measures could be none other than the means of improving the design, manufacturing, or operation of the PRC Long March 3B rocket. By extension, these improvements could improve the design, manufacture, or operation of other PRC rockets as well, and, less directly, of present or future PRC military equipment.

Moreover, the charter called for the Independent Review Committee to "*. . . provide the [China Great Wall Industry Corporation] with copies of any and all working papers collected during its review process.*" [Emphasis added]

It is important to recognize that one of the benefits of a comprehensive accident investigation is that many potentially faulty design features, parts, or procedures ("accidents waiting to happen") may be found and corrected, whether or not they can actually be shown to have played any part in the accident under investigation.

A recent example is that in the investigation of the flight failure of TWA 800, deficiencies were found in the electrical systems of the fuel tank pumps that might have caused or contributed to the failure, or might be the cause of a failure in the future. These deficiencies are being corrected in spite of the fact that they have not been proved to be the cause of the accident.

Thus, included in this assessment are information and advice to the PRC on correcting faults or deficiencies in the design, manufacture, or operation of the Long March 3B, and on improving PRC quality assurance and reliability — as well as information and advice that could apply to PRC rockets or ballistic missiles with design features similar to the Long March 3B — whether or not they are related to what was ultimately determined to be the most likely cause of the Long March 3B accident.

In the period after the Independent Review Committee activities were terminated, the PRC participants, continuing their "hardware in the loop" simulations, found that even with artificially-imposed making and breaking of contact of the electrical connection to the *inner* frame gimbal torque motor, they could not simulate the periodic behavior of the inertial platform for the entire 22-second flight duration.

As later reported by the PRC participants, the series of "hardware in the loop" simulations and analyses that took place from May 20 to June 20, 1996 led to the identification and verification of the *follow-up* frame gimbal axis torque motor circuit as the site of the failure. They did find that by breaking the circuit to the *follow-up* frame torque motor, the entire 22 seconds of flight including the cyclic motions of the inertial platform could be simulated.

The conclusion was then reached that the root cause of the failure was to be found in the electrical circuits associated with the *follow-up* frame gimbal torque motor.

According to PRC officials, examination of these circuits in inertial measurement units from the same production batch as that aboard the failed flight of the Long March 3B led to the discovery of a faulty gold-aluminum junction in the power module that drove this torque motor. The deterioration of the gold-aluminum joint was cited as the cause of the break in the circuit of the follow-up frame gimbal torque motor that led to the inertial measurement unit failure. These findings and conclusions were briefed to the satellite manufacturing, operating, and insurance communities in October 1996.

In the last Independent Review Committee report sent to the PRC after the committee's second meeting, it was suggested that the making and breaking of electrical contacts was not necessary to explain the cyclic motion of the rocket's inertial platform. Rather, once a circuit failure had occurred, it was possible for the platform to perform a natural limit cycle motion. Limit cycles are a well-recognized phenomenon in the dynamics of mechanical, electrical, and electromechanical nonlinear systems.

Although this argument was introduced while the break in the circuit to the inner frame torque motor was considered to be the most probable root cause for the observed inertial platform behavior, it obviously could apply to any other frame or torque motor.

During the second Independent Review Committee meeting, attention was called to the flat behavior of the angle measurement (resolver) of the follow-up frame. The Independent Review Committee stated that it was "very critical" to explain this behavior.

The PRC participants stated that the flat behavior was due to a bad choice of resolution for this telemetry channel — an explanation they obviously changed their mind about later.

Also in the same meeting, the Independent Review Committee called further attention to the follow-up frame by suggesting the possibility that it might have been frozen — that is, mechanically jammed. Although it did not turn out to be the final explanation, this failure mode could have produced about the same kind of inner frame angle resolver telemetry trace as a break in the circuit powering the follow-up frame gimbal axis torque motor. This was an alternate possible cause for the anomaly in the telemetry trace of follow-up frame angle.

Moreover, in their last report, the Independent Review Committee once more suggested that the PRC look again at the validity of their explanation of the flat trace of the follow-up frame angle resolver.

In its comments, questions, and advice on the inertial measurement unit failure mode, and on the simulations and analyses conducted to establish that mode, the Independent Review Committee:

- **Consistently rejected the making and breaking of electrical contact** by the wire delivering current to the torque motor for the inner frame as a plausible explanation for the observed cyclic motion of the inertial platform
- **Insisted that, although the wire break in the circuit carrying current to the inner frame torque motor might be**

considered the most probable root cause for the failure, it could not be accepted as conclusive until additional analyses and "hardware in the loop" simulations could demonstrate that the cyclic motions of the inertial platform over the entire 22 seconds of flight could be accounted for on the basis of this cause

- **Forcibly called attention to the indications in telemetry that the follow-up frame angle measurement was flat,** and remained skeptical of the PRC explanations for this anomaly

- **Pointed out that successive making and breaking of electrical contact in a torque motor circuit was not a necessary condition** for development of cyclic motion of the platform

It is, of course, not possible to say how much these technical comments, suggestions, and challenges influenced the PRC. But they were all in the direction of moving the PRC representatives away from their fixation on the broken wire in the inner frame gimbal axis torque motor as the predominant, if not sole, failure mode to which they had given significant attention in their investigation since mid-March.

Another area that the Independent Review Committee focused on was reliability and quality assurance. In their plant tours, several of the Independent Review Committee members saw what they considered to be flight inertial measurement unit hardware being carelessly handled and touched. In the preliminary report, in the short term, the Independent Review Committee recommended that higher quality control and quality standards be applied in the manufacturing process.

In the detail design of the inertial platform wiring, the Independent Review Committee recommended studies to either preclude wiring harness motion during gimbal motion, or alleviate the effect of unavoidable deflection on solder joint integrity.

Also, the Independent Review Committee recommended that the PRC reexamine the environmental conditions (vibration, noise, and thermal) used in qualification and acceptance testing of the inertial measurement unit.

The distinction between qualification tests and acceptance tests must be made:

- **Qualification tests** are a part of the design and development of the inertial measurement unit. Their purpose is to verify the basic design and manufacturing processes. A high degree of fidelity in simulating flight environments is sought in qualification testing.

- **Acceptance tests** are carried out on *each unit* produced. Acceptance test environments are generally at lower levels of intensity than qualification tests. Depending upon the particulars of specific designs and their potential vulnerabilities, they may be of lower fidelity in representing flight environments in detail.

In fact, vibration tests as part of acceptance testing may often be regarded as tests of workmanship in production. The Independent Review Committee referred specifically to the workmanship verification function in Attachment IV to the minutes of its second meeting as follows: "Quality control was not thorough; the open wire problem should have been caught earlier in the environmental acceptance or screening test[s]."

For the longer term, the Independent Review Committee recommended that quality control philosophy and practices in fabrication, assembly, and testing should be strengthened and personnel should be trained accordingly. These recommendations would also affect reliability and quality assurance. The committee also recommended that consideration be given to increasing the redundancy of the platform.

While these recommendations of improved quality control and greater redundancy can be regarded as general maxims for achievement of improved reliability, it must be borne in mind that they are being made in the context of the expert Independent Review Committee's detailed review of the deficiencies in design, manufacture and testing of the specific inertial measurement unit on the Long March 3B.

The Independent Review Committee also made recommendations concerning the vibration, acoustic, and thermal environments to which the inertial measurement unit (and other avionics) were designed and tested. In their last report, they recommended that the PRC reexamine their environmental test plan for all avionics equipment, expressing the view that the tests might not be adequate for meeting "expected maximum flight loads including acoustic noises or detecting the defects in flight hardware."

The Intelsat 708 Encryption Boards Were Never Recovered

The Intelsat 708 satellite carried two FAC-3R encryption boards, one in each of its command processor units. These boards are considered Controlled Cryptographic Items by the Department of Defense, and the algorithm is classified "Secret."

Encryption boards are used to protect the command and control links between the ground station and satellite. They are required even on satellites that carry unclassified U.S. Government communications traffic. These devices do not encrypt the communications traffic that is otherwise processed by the satellite payload.[374]

Shortly after the Intelsat 708 launch failure, Loral's Communications Security custodian reported to the Department of Defense that the status of the encryption boards was being changed to "destroyed."

This was not seen as unusual by Department of Defense, however, because its prescribed policy requires that encryption boards be reported as "destroyed" when they are launched into orbit.

The Department of Defense did not require Loral to produce any evidence that the FAC-3R boards were in fact destroyed.[375]

After recovering debris from the crash site, Loral engineers grossly estimated the percentages of various subsystems and components that had been recovered.[376] In that estimate, Loral engineer Muhammad Wahdy estimated that 30% of the command processors were recovered.[377] Loral personnel then packaged the debris and shipped it to Palo Alto, where engineers examined the debris to specifically determine if the encryption boards were recovered.[378]

That examination determined that the FAC-3R boards were not, in fact, recovered from the crash site.[379]

The two FAC-3R encryption boards used on the Intelsat 708 satellite were mounted near the hydrazine propellant tanks and most likely were destroyed in the explosion. Additionally, the two FAC-3R boards had no distinguishing markings other than a serial number, making it extremely difficult to locate them amongst the crash debris.[380]

It is not known, however, whether the FAC-3R boards were recovered by the PRC. If they were, it would be difficult for the PRC to determine the cryptographic algorithm that was imprinted on them.

Reverse-engineering of a damaged board would be even more difficult. Any successful reverse-engineering would be resource intensive for the PRC.

If the PRC were able to determine the cryptographic algorithm contained on the FAC-3R board, it would gain insight into the state of the U.S. military in the 1960s, although such algorithms remain in use today.[381]

When the National Security Agency designs and recommends algorithms for use in equipment, it assumes that the equipment will be lost or compromised sometime during its operational lifetime. The National Security Agency relies on unique cryptographic keys for each separate satellite to keep command and control links secure. Because the FAC-3R boards on Intelsat 708 were uniquely keyed, the National Security Agency remains convinced that there is no risk to other satellite systems, now or in the future, resulting from having not recovering the FAC-3R boards from the PRC.[382]

Summary Assessment

In the period after the Independent Review Committee activities were terminated, the PRC participants, continuing their "hardware in the loop" simulations, rejected their own findings that the cause of the launch failure related to the *inner* frame of the inertial measurement unit. Instead, the PRC followed the path identified for them by the Independent Review Committee to conclude that the true cause of the launch failure was related to the *follow-up* frame.

The PRC engineers found that, even with artificially imposed making and breaking of contact of the electrical connection to the inner frame gimbal torque motor, they could not simulate the periodic behavior of the inertial platform for the entire 22-second flight duration. (As later reported by the PRC, the series of "hardware in the loop" simulations and analyses that led to the identification and verification of the follow-up frame gimbal axis torque motor circuit as the site of the failure took place from May 20 to June 20, 1996.)

The PRC participants then concluded that the root cause of the failure was to be found in the electrical circuits associated with the follow-up frame gimbal torque motor. The PRC engineers found that by breaking the circuit to the follow-up frame torque motor, the entire 22 seconds of flight, including the cyclic motions of the inertial platform, could be simulated.

According to the PRC engineers, examination of these circuits in inertial measurement units from the same production batch as the one used on the failed flight led to the discovery of a faulty gold-aluminum junction in the power module that drove this torque motor. The deterioration of the gold-aluminum joint was cited as the cause of the break in the circuit of the follow-up frame gimbal torque motor that led to the inertial measurement unit failure. These findings and conclusions were briefed to the satellite manufacturing, operating, and insurance communities in October 1996.

The Independent Review Committee's comments and suggestions could well have helped the PRC to come to the correct conclusion in their accident investigation more directly and quickly than they otherwise would have.

Taken together, the following actions by the Independent Review Committee would have had the effect of steering the PRC investigators away from their protracted narrow focus on the wrong failure mode:

- **The Independent Review Committee's continuing skepticism** concerning the make-and-break of electrical contact in the connection to the inner frame axis torque motor as a plausible explanation of the observed telemetry data (this was the PRC participants' initial explanation for the launch failure)

- **The committee's insistence that the failure mode investigation could not be considered complete and convincing** until the entire 22 seconds of flight had been simulated (in contrast to the PRC participants' initial reliance on data from only the first seven seconds of flight)

- **The committee's pointing to the existence of dynamical limit cycles of platform motion that could result from a single break** in a torque motor circuit, without repeated making and breaking of electrical contact (again in contrast to the PRC participants' approach)

- **The committee's persistent calling of attention to the potential significance of the flat output of the follow-up frame** angle resolver (the actual location of the cause of the launch failure)

The search for the true failure mode in an accident investigation is not a simple, straightforward procedure. In some respects, it is like finding the way through a maze. It is all too easy to start down a wrong path and to stay on it for too long. Insights, hunches, and clues based on technical judgments and experience in prior failure mode analyses, simulations, and accident investigations can be helpful. Advice from individuals or groups drawn from outside the program that has suffered a failure is often sought, even in organizations that have world-class technical competence. Even opinions from such an outside group confirming that the investigation is on the right track have value.

In the complex task of failure investigation, the right failure mode and adequate corrective measures are often not arrived at the first time. Sometimes there are repeated failures from the same cause because the failure mode analysis was inaccurate or incomplete. (An example was the failure of the PRC Long March 2E fairing, first in the Optus B2 launch in 1992, and then again in the Apstar 2 failure in 1995.) Absent a dissenting view voiced by an authoritative independent group such as the Independent Review Committee, the pressures for getting on with the next launch of the Long March 3B could have prevailed, the flawed analysis of the failure mode could have been accepted, and another failure could have resulted. At the least, the contribution of the Independent Review Committee to the PRC accident investigation may have been simply to speed up the investigation.

The Independent Review Committee's recommendations seem to have affected PRC rocket reliability. The PRC briefed subsequent Long March launch customers and their insurers (for example, in the case of Loral's Mabuhay satellite launch) concerning measures being taken to improve the reliability of the Long March 3B inertial measurement unit (and avionics generally) and acceptance testing.

The measures the PRC took to improve the reliability of the Long March 3B go beyond those listed in the PRC briefings at the second meeting of the Independent Review Committee in Beijing (some of which may have been influenced by questions raised earlier by the committee). For example, in the Beijing meeting, wiring connections on the platform were to be double-soldered. The later briefings indicate that all platform-moveable connections are to be double-jointed (a stress-relieving measure of the type referred to in the Independent Review Committee report's recommendation to "alleviate the impact of unavoidable deflection on solder joint integrity") and double-wired.

Also, the recommendation of the Independent Review Committee for steps to attack quality control philosophy and practice broadly, and to train personnel, are reflected in the PRC statement of intent to strengthen education in quality control for all employees, and to establish income incentives to quality. These measures to improve quality control and reliability may be the standard fare of management literature, but the context of the Independent Review Committee recommendations is that they are made with regard to a specific set of processes and practices employed in the manufacture and assembly of the Long March 3B that they reviewed.

To the extent that these practices and processes are representative of those employed on other rockets or ballistic missiles or their components built by the same or related organizations, the quality control and *reliability* of these PRC rockets and missiles could also be improved.

To answer definitively whether the Independent Review Committee's technical advice and recommendations had the effect of assisting the PRC in improving the *accuracy* of PRC ballistic missiles, it would be necessary to know whether the Long March 3B inertial measurement unit is used on any ballistic missile and whether, in fact, the Long March 3B inertial measurement unit has advantages in accuracy or other measures over others available to the PRC. The guidance accuracy requirements for an intercontinental ballistic missile based on what is assumed to be PRC missile doctrine (essentially, a "city busting" strategy) would not be considerably greater than the accuracy requirements for a rocket used to launch satellites. Because the Long March 3B inertial measurement unit is lighter and smaller than the units used on the PRC's intercontinental ballistic missiles (such as the currently-deployed CSS-4), it would not need to have greater accuracy to be advantageously applied for its weight and size advantages.

Because the PRC strategic forces doctrine apparently targets U.S. cities, this does not require especially demanding accuracy. For this, the inertial measurement unit on the Long March 3B may be sufficient — in which case its size, weight, and, potentially, reliability advantages may weigh more heavily in its favor. Of course, if the PRC has available other lighter and smaller guidance units that are more accurate, those are more likely to be chosen for the mobile intercontinental ballistic missile mission.

For shorter-range ballistic missiles, the Long March 3B inertial measurement unit might possibly be advantageously used. But it would have to compete against a variety of even more compact, strapdown systems of sufficient accuracy for short ranges. Therefore, the application of the Long March 3B inertial measurement unit or some variant of it to some future PRC ballistic missile development remains possible.

To the extent that ballistic missile manufacturing processes and practices are similar to those for rockets, an incremental potential benefit to future PRC ballistic missile programs could come from increased production efficiency, and improved reliability through adoption of improved quality control and reliability-enhancing measures in design and manufacturing that were introduced after the accident investigation, including some that the Independent Review Committee advocated.