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EXECUTIVE SUMMARY

On 30 April 1999, at 12:30 hours EDT, a Lockheed Martin Astronautics Titan IV B configuration vehicle (Titan IV B-32), with a Titan Centaur upper stage (TC-14), launched from Space Launch Complex 40, at Cape Canaveral Air Station, Florida. The mission was to place a Milstar satellite in geosynchronous orbit. The flight performance of the Titan solid rocket motor upgrades and core vehicle was nominal. The Centaur separated from the Titan IV B approximately nine minutes and twelve seconds after lift-off. The vehicle began experiencing instability about the roll axis during the first burn. That instability was greatly magnified during Centaur's second main engine burn, coupling each time into yaw and pitch, and resulting in uncontrolled vehicle tumbling. The Centaur attempted to compensate for those attitude errors by using its Reaction Control System, which ultimately depleted available propellant during the transfer orbit coast phase. The third engine burn terminated early due to the tumbling vehicle motion. As a result of the anomalous events, the Milstar satellite was placed in a low elliptical final orbit, as opposed to the intended geosynchronous orbit.

The Accident Investigation Board concludes by clear and convincing evidence that failure of the Titan IV B-32 mission is due to a failed software development, testing and quality assurance process for the Centaur upper stage. That failed process did not detect and correct a human error in the manual entry of the I1(25) roll rate filter constant entered in the Inertial Measurement System flight software file. The value should have been entered as –1.992476, but was entered as –0.1992476. Evidence of the incorrect I1(25) constant appeared during launch processing and the launch countdown, but its impact was not sufficiently recognized or understood and consequently, not corrected before launch. The incorrect roll rate filter constant zeroed any roll rate data, resulting in the loss of roll axis control, which then caused loss of yaw and pitch control. The loss of attitude control caused excessive firings of the Reaction Control System and subsequent hydrazine depletion. Erratic vehicle flight during the Centaur main engine burns caused the Centaur to achieve an orbit apogee and perigee much lower than desired. The Milstar satellite separated in a useless low final orbit. After several days of satellite life saving effort by Air Force and satellite contractor personnel at Schriever Air Force Base, Colorado, the Milstar satellite was declared a complete loss by the acting Secretary of the Air Force on 4 May 1999. The Accident Investigation Board concludes the root cause is the result of several contributing factors:

Software Development

- The software development process is not well defined, documented, or completely understood by any of the multiple players involved in that process.
- The lack of focus and understanding of Inertial Measurement System software operations and Inertial Navigation Unit testing contributes to the poorly defined process for generation and test of the I1 rate filter constants.
- The software development process allows single point failures for mission critical data.
- The consolidation of the major contracting companies responsible for Titan/Centaur development and the maturation of the Titan/Centaur program contribute to the poor understanding of the overall software development process.

Testing, Validation and Verification

- An independent verification and validation program was developed and approved that does not verify or validate the I1 filter rate constants used in flight.

- No formal processes exists to check validity of the I1 filter constants or monitor attitude rates once the flight tape is loaded in the Inertial Navigation Unit at Cape Canaveral Air Station prior to launch.

- Inadequate and indirect communication among the responsible parties prevented correction of the problem observed during testing at Cape Canaveral Air Station prior to launch.

Quality/Mission Assurance

- A software quality assurance function exists at both Lockheed Martin Astronautics and Defense Contract Management Command, but operates without a detailed understanding of the overall process or program. In addition, transition from oversight to insight is not implemented properly because of that lack of understanding.

- The Space and Missile Systems Center Launch Directorate and the 3rd Space Launch Squadron have undergone personnel reductions and are transitioning from a task oversight to process insight role. That transition has not been managed by a detailed plan. Air Force responsibilities under the insight concept have not been well defined and how to perform those responsibilities has not been communicated to the workforce.

J. GREGORY PAVLOVICH, Colonel, USAF
Accident Investigation Board President

DISCLAIMER

Under 10 U.S.C. 2254(d), any opinion of the accident investigators as to the cause or causes of, or the factors contributing to, the accident set forth in the accident investigation report may not be considered as evidence in any civil or criminal proceeding arising from a launch vehicle accident, nor may such information be considered an admission of liability by the United States or by any person referred to in those conclusions or statements.

ACRONYM LISTING

AF	Air Force
AFB	Air Force Base
AFI	Air Force Instruction
AFSPC	Air Force Space Command
AIB	Accident Investigation Board
CCAS	Cape Canaveral Air Station
CD	Control Dynamics
DCMC	Defense Contract Management Command
EAT	Engineering Analysis Team
EDT	Eastern Daylight Time
FAST	Flight Analogous Simulation Test
FCS	Flight Control System
FDACAR	Flight Dynamics and Control Analysis Report
FS	Flight Software
FTS	Flight Termination System
GHe	Gaseous Helium
GMT	Greenwich Mean Time (or Zulu = EST + 5 hours)
IMS	Inertial Measurement System
INU	Inertial Navigation Unit
ISO	International Organization for Standardization
ISP	Specific Impulse
IV&V	Independent Verification and Validation
JA	Judge Advocate
LH2	Liquid Helium
LO2	Liquid Oxygen
LMA	Lockheed Martin Astronautics
MS	Missile Squadron
PIE	Product Integrity Engineer
PA	Public Affairs
RCS	Reaction Control System
SIB	Safety Investigation Board
SLS	Space Launch Squadron
SMC	Space and Missile Systems Center (Los Angeles AFB, CA)
SRMU	Solid Rocket Motor Upgrade
SW	Space Wing
TC	Titan Centaur
UHF	Ultra High Frequency
WT	Weight
Z	Zulu (or Greenwich Mean Time)

FORMAL REPORT OF INVESTIGATION

I. AUTHORITY AND PURPOSE

At the direction of the Commander, Air Force Space Command, an investigation of the 30 April 1999 Titan IV B/Centaur TC-14/Milstar-3 (B-32) space launch mishap was conducted. The investigation team consisted of the following:

Accident Investigation Board:

Colonel J. Gregory Pavlovich
President
341 SW/CC; Malmstrom AFB, MT

Colonel Charlotte L. Rea-Dix
Vice President
SMC/AD; Los Angeles AFB, CA

Both Colonel Pavlovich and Colonel Rea-Dix possess knowledge and expertise relevant to space launch accident investigations. Colonel Pavlovich attended the Air Force Safety Center Board President's Course.

Technical Advisors:

Captain Harold Rollins
12 MS; Malmstrom AFB, MT

Captain Joseph Taffe
564 MS; Malmstrom AFB, MT

Dr. George Widhopf
Aerospace Corp.; Los Angeles, CA

MSgt Joseph J. Shrum
14 AF; Vandenberg AFB, CA

Legal Advisor:

Captain Michael J. McCormick
341 SW/JA; Malmstrom AFB, MT

Recorder:

Captain Ronald D. Ten Haken
341 SW/CCE; Malmstrom AFB, MT

Public Affairs:

Mr. Ed Parsons
AFSPC/PA; Peterson AFB, CO

The purpose of the accident investigation was to gather and preserve evidence for claims, litigation, disciplinary and adverse administrative actions, and for all other purposes in accordance with AFI 51-503, *Aircraft, Missile, Nuclear, and Space Accident Investigations*, dated 1 December 1998. The investigation was also tasked to present a summary of facts and a statement of opinion regarding the accident.

II. SUMMARY OF FACTS

A. ACCIDENT SUMMARY

On 30 April 1999, at 12:30 hours EDT,[1] mission Titan IV B-32/Centaur TC-14/Milstar-3 launched from Space Launch Complex 40, at Cape Canaveral Air Station (CCAS). The booster was a Titan IV B equipped with a Centaur Upper Stage. The mission was to place a Milstar satellite in geosynchronous orbit. The flight performance of the Titan solid rocket motor upgrade (SRMU) and the core vehicle was nominal, as was payload fairing separation. The Centaur separated from the Titan IV B approximately nine minutes and twelve seconds after lift-off. Approximately 10 seconds into Centaur main engine start, the Centaur vehicle began to exhibit an anomalous roll condition that continued throughout the first burn and into the first coast phase. The vehicle attitude control system was able to stabilize the vehicle during the coast phase, but in doing so expended 85 percent of the Reaction Control System (RCS) propellant. Soon after entering the second burn phase, the vehicle again became unstable about the roll axis. Because the second burn is longer than the first, the excess roll commands saturated pitch and yaw, resulting in loss of pitch and yaw control as well as roll. Due to its uncontrolled tumbling during the burn, the vehicle did not achieve its intended velocity nor reach the correct transfer orbit. During the second coast phase, the attitude control system again tried to stabilize the vehicle but was unsuccessful as it soon exhausted its remaining propellant. The vehicle entered the third burn tumbling and continued to tumble throughout the burn and into the third coast phase. Vehicle separation occurred, but due to the anomalous events the Milstar satellite was placed in an incorrect and unusable low elliptical orbit, as opposed to the desired geosynchronous orbit. Media interest was high due to this mishap being the third straight Titan IV failure, and recent failures of other commercial space launches.

B. BACKGROUND

The 3SLS, CCAS, Florida, was the Air Force unit in charge of the launch of the Titan IV B-32/Centaur TC-14/Milstar-3 mission. It reports to the 45th Space Wing, Patrick AFB, Florida. Lockheed Martin Astronautics (LMA) was the prime contractor for the mission. The Space and Missile Systems Center Launch Directorate (SMC) was responsible for insight and administration of the LMA contract. The Titan IV B-32 mission was to place the third Milstar spacecraft into a predetermined geosynchronous orbit.

C. LAUNCH VEHICLE AND SATELLITE DESCRIPTIONS

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[1] EDT = Eastern Daylight Time will be the primary clock reference; references to events occurring during flight will be referenced as time elapsed after lift off, T+ hh:mm:ss.

Titan IV B[2]

The Lockheed Martin Titan IV B is a heavy-lift space launch vehicle used to carry government payloads such as Defense Support Program, Milstar, and National Reconnaissance Office satellites into space. It is launched from CCAS, Florida and Vandenberg Air Force Base, California. The vehicle can be launched with no upper stage, or with one of two optional upper stages, providing greater and varied capability. The two types of upper stages are the Centaur Upper Stage and the Inertial Upper Stage. The Titan IV B can carry up to 47,800 pounds into a low-earth orbit and up to 12,700 pounds into a geosynchronous orbit when launched from CCAS using the Centaur Upper Stage. See Figure 1 for a schematic of the launch vehicle.

Figure 1

Centaur Upper Stage[3]

The Lockheed Martin Astronautics Centaur is a cryogenic, high-energy upper stage. It can achieve park orbit and transfer spacecraft to higher orbits. The Centaur uses two Pratt-Whitney RL-10 rocket engines, fueled by liquid hydrogen and oxygen, to develop approximately 33,000 pounds of vacuum thrust. The engines are capable of making multiple restarts after long coast periods in space to achieve park orbit and provide transfer for satellite deployment. The Centaur carries its own guidance, navigation and control system, which measures the Centaur's position and velocity on a continuing basis throughout flight. It also determines the desired orientation of the vehicle in terms of pitch, yaw and roll axis vectors. It then issues commands to the required control components to orient the vehicle in the proper attitude and position, using the main engine or the RCS engines. The RCS provides thrust for vehicle pitch, yaw and roll control, for post-injection separation and orientation maneuvers, and for propellant settling prior to engine restart. See Figure 2 for a diagram of the Centaur.

Figure 2

For additional information on Titan IV and Centaur, refer to figure 7 on page 27.

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[2] Additional information concerning the Titan IV B can be obtained at www.spacecom.af.mil
[3] Additional information concerning the Centaur Upper Stage can be obtained at www.spacecom.af.mil

Milstar Satellite[4]

Figure 3

Milstar is a joint service satellite communications system that provides secure, jam resistant, worldwide communications to meet essential wartime requirements for high priority military users. Milstar is the most advanced military communications satellite system to date. The multi-satellite constellation will link command authorities with a wide variety of resources, including ships, submarines, aircraft and ground stations. A key goal of Milstar is to provide interoperable communications among the users of Army, Navy, and Air Force Milstar terminals. The first Milstar satellite was launched 7 February 1994. The second was launched 5 November 1995. This mission was the third launch.

D. HISTORY OF THE MISSION

Assembly and Pre-Launch [5]

The core vehicle for Titan IV B-32 arrived at Cape Canaveral Air Station on 9 July 1998. It was rolled into the Solid Motor Assembly and Readiness Facility on 22 September 1998 for the Solid Rocket Motor Upgrade mate. It was rolled to the launch pad on 5 October 1998, and LMA personnel at CCAS mated the Centaur to the launch vehicle on 16 October 1998. The Terminal Countdown Demonstration Test was accomplished on 28 January 1999. The Milstar satellite was mated to the Centaur on 17 February 1999. The Launch Combined Systems Test took place on 19 April 1999. Launch was on 30 April 1999.

A number of booster problems were identified by the Titan IV B-32 launch team prior to launch to include: a dead face umbilical issue, a 5 Amp-hr battery concern, high energy firing unit failure, non-commanded shifts during testing of the roll control actuator, and a nozzle shift data concern. All of these problems were resolved satisfactorily by the time of launch. None were relevant to the mishap.

The Titan IV B-32 launch team also identified a number of problems/concerns with the Centaur during launch processing. Those included improper installation of the UHF Circulator on the Flight Termination System, six wire harness discrepancies, Pratt and Whitney pedigree verifications for idler bearings and impeller cracks, and cracked diodes on the Inertial Navigation Unit. All of those problems were resolved satisfactorily prior to launch. None were relevant to the mishap.

Launch [6]

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[4] Additional information concerning the Milstar satellite can be obtained at www.spacecom.af.mil
[5] Information regarding launch processing was obtained from the Launch Readiness Review

Processing for the Titan IV B-32/Centaur TC-14/Milstar-3 Mission proceeded with the Launch Readiness Review accomplished on 29 April 1999. The terminal countdown clock started on 29 April 1999 at 2136 EDT. Weather was a factor during the countdown process.[7] Complex 40 was cleared for an hour and a half due to a lightning warning. An abnormal sniff check reading for hazardous vapors also delayed the launch. Liftoff occurred at 1230 hours EDT, 30 April 1999. All weather factors were well within constraints at the time of liftoff. The temperature was 74° F and there were occasional showers and scattered clouds. The wind direction was 340° at 15 to 20 knots. There were no ground, wind, or lightning strike violations. Liftoff was nominal.

Flight [8]

The flight proceeded normally up to Titan/Centaur separation at T+ 00:09:12.[9] The SRMUs' performance and separation were as expected. Stage I performance was nominal. The Payload Fairing jettisoned as planned. Titan Stage I and Stage II separated at T+ 00:05:24. The Stage II flight exhibited a few abnormal conditions, but none impacted the mission or were relevant to the mishap. Stage II shut down as planned.

The Centaur separated from the Titan at approximately T+ 00:09:12. The separation was as expected and the Centaur was injected into its orbit satisfactorily. Data from both the Titan and Centaur navigational systems verified the injection was nominal. Centaur body rates were as expected through tip-off and pre-start.

There were three planned burns during the Centaur flight. The first burn would put the Centaur into a parking orbit. The second would move the Centaur into an elliptical transfer orbit that would carry the Centaur and the satellite to geosynchronous orbit. The third and final burn would circularize the Centaur in its intended geosynchronous orbit. A coast phase was planned between each burn. During the coast phase the Centaur would progress under its own momentum to the proper point in the orbit for the next burn. The Centaur would also exercise a roll sequence, and attitude control maneuver during the coast periods to provide passive thermal control, and settle the main engine propellants in the bottom of the tanks.

The first burn occurred at approximately T+ 00:09:30, as planned. Throughout the flight, the Inertial Measurement System (IMS) transmitted zero or near zero roll rate to the Flight Controller software. With no roll rate feedback, the Centaur became unstable about the roll axis and did not roll to the desired first burn orientation. The Centaur began to roll back and forth, eventually creating sloshing of the vehicle liquid fuels in the tanks that created unpredictable forces on the vehicle, and adversely affected flow of fuel to the engines. By the end of the first burn (approximately T+ 00:11:35), the roll oscillation began to affect the pitch and yaw rates of the vehicle as well.

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[6] See Tab K-2
[7] See Tab U-1 (Statement of Sauter); Y-1 (EAT Report)
[8] See Tab Y-1. The EAT Report provides further details regarding the Flight.
[9] All times used in the Summary of Facts will be T+ hours:minutes:seconds after lift-off.

Vehicle tumbling and fuel sloshing affected the attained vehicle acceleration, resulting in the Centaur guidance system predicting an incorrect time for main engine shutdown. Centaur's first burn did not achieve the intended velocity, and consequently the vehicle was placed in an unintended park orbit. With first burn shutdown complete, the Centaur entered the first coast phase of the flight. Due to roll instability and transients created by the engine shutdown, the Centaur entered the coast period tumbling. The RCS immediately attempted to stabilize the vehicle. Late in the park orbit, the Centaur was finally stabilized about the pitch and yaw axes, although it continued to oscillate about the roll axis. The stabilization came at the cost of almost 85 percent of the RCS propellant. The vehicle successfully pointed at the proper attitude for the second burn, and the engines ignited at approximately T+ 01:06:28.

Soon after the second burn was initiated, as in the first burn, the vehicle began a diverging roll oscillation. Since the second burn is longer than the first, the roll commands eventually saturated the pitch and yaw channels. At approximately two minutes into the second burn, pitch and yaw control was lost, causing the vehicle to tumble for the remainder of the burn. The uncontrolled tumbling caused the vehicle not to achieve the planned acceleration for transfer orbit.

The Centaur continued to tumble in the transfer orbit despite the RCS's continued attempts to stabilize the vehicle. The RCS depleted its remaining propellant approximately 12 minutes after shutdown of the second burn. The vehicle's third burn started at T+ 02:34:15. The vehicle tumbled throughout the third burn, which started earlier, and was shorter than programmed. Space vehicle separation occurred at approximately T+ 02:54:15. The Milstar satellite achieved a final low elliptical orbit rather than the intended geosynchronous orbit. See Figure 4 below.

Space Vehicle Activity[10]

The Centaur upper stage failed to put the Milstar satellite in a proper orbit to function as designed. The Mission Director ordered early turn-on at T+ 01:17:00. The controllers were unable to contact the satellite for approximately 3 hours. At T+ 06:14:00, control was acquired and various survival and emergency actions taken. Although the mission was officially declared a failure on 4 May 1999, personnel from LMA and the 4th Space Operations Squadron at Schriever AFB, Colorado controlled the satellite for six additional days in order to place the satellite in a non-interfering orbit with minimum risk to operational satellites. The satellite was damaged from the uncontrolled vehicle pitch, yaw and roll movements and high acceleration rates of the Centaur. There were no possible actions the ground controllers could have taken in response to the anomalous events that would have saved the mission. It appears the satellite performed as designed, despite the anomalous conditions. The satellite was shut down on 10 May 1999.

Media Interaction

Under AFI 51-503 and the Space Launch Vehicle Mishap Investigation Policy, Air Force public affairs released information about the mishap to local, national and international media via a press conference on 1 May 1999 and subsequent press releases. Unidentified sources did provide *Aviation Week & Space Technology* and other news agencies information on the software problem. Media coverage during the investigation appeared focused on the string of space launch mishaps rather than just the Titan IV B-32 failure. Selected press coverage excerpts can be found in Tab V.

D. FACTUAL RESULTS FROM INVESTIGATION

Investigation Team Description

Pursuant to the Space Launch Vehicle Mishap Investigation Policy adopted by the Acting Secretary of the Air Force on 16 February 1998, an Accident Investigation Board (AIB) and a Safety Investigation Board (SIB) were appointed concurrently and ran a dual track investigative process. Under that process, an Engineering Analysis Team (EAT), composed of Lockheed Martin Astronautics, United States Air Force and Aerospace Corporation personnel conducted the technical analysis of the mishap. The AIB and SIB oversaw the analysis to ensure it was thorough and impartial. The engineering analysis of the EAT was not binding on the AIB or SIB. Either board could supplement the EAT analysis, order or conduct additional testing, or conduct further investigation if necessary. The AIB and SIB had unrestricted access to all meetings of the EAT, the contractor's work sites and to contractor personnel.

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[10] Events Review Board 4th Space Operations Squadron/LMA Report

Investigative Process

The technical investigation consisted of an expanded Ishikawa cause and effect analysis, commonly referred to as a "fishbone" analysis. From the beginning, the software-input error was suspected as the most likely cause of the mishap. Still, it was necessary to do a thorough investigation and consider all possibilities. That was done to ensure there were no other contributing causes that could lead to other anomalies in the future, and to validate the suspicion that the software input error was the cause. The investigation did consider several other possibilities, but all were ruled out as contributors to the mishap.

Investigation Findings

On 5 February 1999, an LMA flight software engineer incorrectly entered a roll rate filter constant into the Inertial Navigation Unit software file. The error went undetected by both the internal quality assurance processes and the independent verification and validation (IV&V) process. The digital roll rate filter is an algorithm with five constants. The filter was designed to prevent the Centaur from responding to the effects of Milstar fuel sloshing and inducing roll rate errors at 4 radians/second. Early in the design phase of the first Milstar spacecraft, the manufacturer asked to filter that frequency. The spacecraft manufacturer subsequently determined filtering was not required at that frequency and informed LMA. However, LMA decided to leave the filter in place for the first and subsequent Milstar flights for consistency.

The correct value of the filter constant was ≅ -1.992476. The specific flight constant entered in error was the I1(25) constant. It was one of forty constants in a file commonly referred to as the I1s. It was incorrectly entered as I1(25) ≅ -0.1992476. The incorrect I1(25) constant went undetected during the sign-off process by the responsible LMA Control Dynamics engineer and became part of a baseline file used for generating all flight software. The software input error was the catalyst for the mishap. The root cause of the mishap was the software development process that allowed a human error to go undetected.

After reviewing the software development process and interviewing the primary participants, the AIB retraced the sequence of events that led to the mishap. The overall process flow depicted in Figure 5 is a flowchart developed by LMA after the Titan IV B-32 mishap. The letters in gray circles identify key points in the process and correspond to the paragraphs that follow.

A. The software Constants and Code Words Memo was generated by the LMA Control Dynamics (CD) group and sent to the LMA Centaur Flight Software (FS) group on approximately 23 December 1997. It provided the intended and correct values for the first I1 constants in hardcopy form. The memo also allocated space for 10 other constants to be provided by the LMA Avionics group at a later time. It also specified a path and file name for an electronic version of the first 30 constants. The memo did not specify or direct the use of either the hardcopy or electronic version for creating the constants database.[11]

B. The LMA Centaur FS group responsible for accumulating all the software and constants for the flight load was given discretion in choosing a baseline data file. Some manual manipulation of the input data was required. No specified or documented software development process existed for electronically merging all the inputs into a single file. When the FS engineer tried to access the file specified in the software Constants and Code Words Memo, it no longer existed at the specified location on the electronic file folder because it was now over a year after the file was originally generated. The FS engineer selected a different file as a baseline that only required him to change five I1 values. During manual entry of

[11] See Tabs U-3, U-4, X-2

those five I1 roll rate filter values, the FS engineer incorrectly entered or missed the exponent for the I1(25) constant. The exponent should have been a 1 instead of a 0 making the entered constant 1/10th of the intended value. That value became part of the file that was used to automatically build the Sign-off Report, Firing Tables Report and the Flight Load tape for use at CCAS. The FS engineer's immediate supervisor did not check the software manual entry. The Flight Load tape was not used in the LMA Flight Analogous Software Test (FAST) test bed. That I1 file was not sent to Analex-Cleveland for autopilot validation since Analex-Cleveland only performs design validation.[12]

C. On or about 17 February 1999, the FS engineer who developed the Flight Load tape notified the CD engineer responsible for design of the first thirty I1 constants that the tape was completed and the printout of the constants was ready for inspection. The CD engineer went to the FS offices and looked at the hardcopy listing to perform the check and sign-off the I1 constants. The manual and visual check consisted of comparing a list of I1 constants from Appendix C of the software Constants and Code Words Memo to the paper printout from the Flight Load tape. The formats of the floating-point lists were different for each list. The CD engineer did not spot the exponent error for I1(25) and signed off that the I1 constants on the Flight Load tape were correct. The CD engineer's immediate supervisor, the lead for the CD section, did not review the Sign-off Report or catch the error.[13]

D. The tapes sent to FAST did not contain the Inertial IMS filter constants because FAST did not use the flight values, only a set of generic default values. The FAST lab was originally constructed with the capability to exercise the actual flight values for the filter constants, but that capability was not widely known by the current FAST personnel until after the Titan IV B-32 mishap. FAST testing was used predominantly to test Flight Control software developed by LMA. IMS software was provided by Honeywell, who verified and validated it.[14]

E. The flight load tape was sent to LMA engineers at CCAS, Analex-Denver and Aerospace shortly after sign-off on 17 February 1999. Analex-Denver did a range and bit check, and the value for the I1(25) constant was within the range of acceptable values.[15]

F. Analex-Cleveland received the Flight Dynamics and Control Analysis Report (FDACAR), containing the correct value for the roll filter constant. Their function is to validate the autopilot design values provided in the FDACAR. That does not include IV&V of the I1 constants in the flight format. The original design work is correctly represented by the constants in the FDACAR. In other words, the filter constant in question was listed in the FDACAR with its correct value of ≅ -1.992476, and not the value which was on the flight tape ≅ -0.1992476. Analex-Cleveland verifies functionality of the design constant and not what is loaded into the Centaur for flight.[16]

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[12] See Tabs U-3, U-4, U-6, X-1
[13] See Tabs U-3, U-4, X-1
[14] See Tabs U-4, U-14, X-1
[15] See Tabs X-1, U-12, U-13
[16] See Tabs X-1, U-12

G. The FAST lab was designed to test the compatibility and functionality of the Flight Control software and the Honeywell IMS software. The FAST lab used a simulation for the IMS filters built on the original, correctly specified values from the LMA CD engineer. It did contain the actual Flight Control software, but not the IMS filter constants as entered by the software personnel in the generation of the Flight Load tape. With a mix of actual flight software and simulated filters, the I1(25) error was not present and not detected during internal LMA testing before the Titan IV B-32 mishap.[17]

H. Analex-Denver used IMS default values for testing for several reasons. The I1 constants were accepted as part of the "truth baseline" provided by LMA, per agreement between LMA and Analex. Analex did not realize part of the I1 constants were manually entered and manipulated during the generation of the flight tape. Analex-Denver also did not validate the actual I1 constants used in flight. They believed their rigid body simulation of the vehicle would not exercise the filters sufficiently. After the launch failure, Analex-Denver found that had they tested all the flight I1 constants, they would have seen the error. For their verification effort, Analex-Denver performed a range check of the program constants and Class I flight constants. They also verified the format conversions were done correctly. However, the format conversion they performed simply compared the incorrect I1(25) in the firing tables to the incorrect I1(25) after the conversion, and they matched.[18]

I. The incorrect I1 constant was first loaded into the flight hardware at CCAS on 14 April 1999. The same load of flight software and constants is used each time the Centaur is powered up from that point through launch. The LMA Guidance engineer and a LMA Data Station monitor at CCAS each noticed the roll rate output was very low. They reviewed the results from previously run procedures and correlated the change with the first installation of the actual flight loads on 14 April 1999. Prior to that time, the I1 constants for the previous Titan/Centaur flight (TC-09), which was not a Milstar flight, had been used. The Guidance engineer initially discussed her observations with the LMA (Denver) Product Integrity Engineers (PIEs) for the Inertial Navigation Unit hardware and Inertial Navigation Unit system. The PIEs referred her to the LMA CD lead.[19] (Continued on next page.)

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[17] See Tabs U-6, U-14
[18] See Tabs U-12, U-13, U-14
[19] See Tabs X-1, U-1, U-2, U-3, U8, U-9, U-17, U-18, U-20

On Friday, 23 April 1999, the LMA Guidance engineer telephoned the LMA CD lead. The CD lead was not in his office so the Guidance engineer left a voice mail stating she noticed a significant change in roll rate when the latest filter coefficients were entered, and asked for a return call to her or her supervisor. The Guidance engineer left an e-mail for her supervisor at CCAS explaining the situation. Her supervisor was on vacation, and due back in the office Monday morning 26 April 1999, when she was scheduled to work the second shift. The CD lead and the CD engineer who originally specified the filter values listened to the voice mail from the Guidance engineer. They called her supervisor at CCAS who had just returned from vacation. He was initially unable to find the e-mail during their conversation. He said he would call back, so the CD engineer left the CD lead's office. The CD lead subsequently talked to the Guidance supervisor after he found and read the e-mail. The CD lead told the supervisor at CCAS the filter values had changed in the flight tape originally loaded on 14 April 1999, and the roll rate output should also be expected to change. Both parties believed the difference in roll rates observed were attributable to expected changes with the delivery of the flight tape. LMA (Denver) engineers requested no hardcopy information and did not speak directly with the Guidance engineer or Data Station Monitor.

Figure 6

Figure 6 compares body rate output from a correct flight software load to the output from the software load containing the incorrect I1(25) constant. The top graph depicts pitch, roll and yaw errors for a correctly functioning guidance box with the rocket still sitting on the pad. The effects of wind and the earth's rotation are visible in all three major body axis. The bottom graph depicts the same rate traces for an incorrectly loaded I1(25) constant, also with the rocket still sitting on the pad. In this case, the roll rate is flat lined. No wind effects are felt and the earth's rotation is not being sensed. That flat line roll rate output continues until launch, and throughout flight. Excerpts of this read out for Titan/Centaur-14 at Tab X-3.

Quality/Mission Assurance

Apart from the software development process depicted in Figure 5, a software quality assurance function existed at both LMA and Defense Contract Management Command (DCMC), but operated without a detailed understanding of the overall software development process or program. As a result, transition from an oversight role to an insight role was not correctly implemented. The DCMC personnel performing surveillance on the software development process did not have a clear understanding of the process when they developed their master surveillance plan. They did not understand that manual input of the I1 constants caused a single point failure in the process, and consequently did not identify constants generation as high risk in their surveillance plan. Their risk analysis was not based on determining steps critical to mission success, but on how often problems previously surfaced in particular areas on past launches. They determined software constant generation was low risk because there had not been previous problems in that area. They only verified that the sign-off report containing the constants had all the proper signatures. The SMC Launch Programs Directorate essentially had no organic personnel assigned to monitor or provide insight into the generation and verification of the software development process. The LMA Software Quality Assurance staff left the I1 constant generation and verification process to the FS and CD engineers. Software Quality Assurance involvement was limited to verification of software checksums and placing quality assurance stamps on software products that were produced. The LMA Quality Assurance Plan is a top level document that focuses on verification of process completion, not on how the processes are executed or implemented. Its basis is the original General Dynamics Quality Assurance Plan with recent updates to ensure compliance with ISO 9001. Through corporate mergers and consolidations, most of the General Dynamics personnel responsible for the plans original development are no longer with the program, which contributes to the present lack of understanding of the process. The 3SLS engineers were performing insight on a catch-as-catch can basis since their formal insight plan was still in draft. They used their best engineering judgement to determine which tasks to monitor and how closely to analyze the data from each task. The 3SLS engineers were present during launch processing and launch countdown to observe the data, but did not recognize the roll rate output as anomalous.

The 30 April 1999 failure of the Titan IV B-32 mission was due to a failed software development, testing and quality assurance process for the Centaur Upper Stage. That process failed to detect and correct a human error in the manual entry of the I1(25) roll rate filter constant entered into the IMS flight software file. The AIB concludes the root cause is based upon the above factors.

J. GREGORY PAVLOVICH, Colonel, USAF
Accident Investigation Board President

III. STATEMENT OF OPINION

DISCLAIMER

Under 10 U.S.C. 2254(d), any opinion of the accident investigators as to the cause or causes of, or the factors contributing to, the accident set forth in the accident investigation report may not be considered as evidence in any civil or criminal proceeding arising from a launch vehicle accident, nor may such information be considered an admission of liability by the United States or by any person referred to in those conclusions or statements.

STATEMENT OF OPINION

There is clear and convincing evidence that the 30 April 1999 failure of Titan IV B-32 mission was due to a failed Titan/Centaur software development, testing and quality/mission assurance process. An incorrect parameter in the Centaur Inertial Measurement System roll rate filter, the I1(25) constant, was manually entered into the flight software at an improper value. The value should have been –1.992476, but was entered as -0.1992476. The order of magnitude error resulted in the sensed vehicle roll rate being filtered to a near zero magnitude. The Flight Control System (FCS) receiving the incorrect roll rate values sent incorrect commands to the Centaur engines, causing the vehicle to become unstable during the first burn of the Centaur main engines. The attitude control system was able to stabilize the system in the coast period prior to initiation of the second burn, but in doing so expended 85 percent of the Reaction Control System (RCS) propellant. During the second burn, the vehicle again became unstable due to the incorrect FCS commands being sent to the main engines, and the engines shutdown before the intended velocity was obtained. That resulted in the Centaur engines not being able to propel the vehicle to the proper transfer orbit. The vehicle instability continued into the subsequent coast period where the Centaur vehicle expended the rest of its RCS propellant in an unsuccessful attempt to stabilize the vehicle. The third main engine burn, which is used to circularize the orbit to geosynchronous altitude, was initiated when the Inertial Navigation Unit (INU) sensed the Centaur approaching apogee. But apogee was achieved three hours earlier and at a much lower altitude than planned due to the anomalous second engine burn. The third engine burn terminated early due to the vehicle tumbling motion preventing the proper flow of propellant to the engines. The faulty third engine burn resulted in the Milstar satellite being separated from the Centaur in an incorrect and unusable orbit. (Figure 4)

The Accident Investigation Board concludes the root cause of the Titan IV B-32 mission mishap was due to the failure of the software development, testing and quality/mission assurance process used to detect and correct a human error in the manual entry of the I1(25) constant. The undetected error resulted in the INU not properly filtering the sensed vehicle roll rates, thus sending incorrect values to the FCS which was then unable to control the vehicle in flight. The AIB concludes the root cause is based on several factors described as follows:

Software Development

a. The software development process used to develop and test the I1 constants actually used in the flight software was not well defined, documented, or completely understood by any of the multiple players involved in that process. The AIB could not identify the single process owner responsible for understanding, designing, documenting, controlling configuration and ensuring proper execution of the process. Prior to the Titan IV B-32 mission failure, there was no formal documentation of the overall process flow as shown in Figure 5. There were multiple players who performed portions of the process, but they only completely understood their specific portion of the process. For example, the Lockheed Martin Astronautics (LMA) Control Dynamics (CD) personnel who design the I1 rate filter constants did not know their design values were manually input into the database used to build the flight tapes. They were not aware that the manually input values were never formally tested in any simulations prior to launch, including the Flight Analogous Simulation Test (FAST), which was actually performed using a 300 Hertz filter simulation data file and not the flight tape values. Thus, simulator testing was not performed as the system was supposed to be flown. The LMA Software Group personnel who create the database, from which the flight tapes are generated, were not aware that Analex Independent Verification and Validation (IV&V) testing did not use the as-flown (manually input) I1 rate filter constants in their verification or validation process. Analex-Denver is responsible for IV&V of the flight software to ensure the autopilot design is properly implemented in the software. Analex-Denver was not aware that the I1 filter rate values provided to them by LMA as the "truth baseline" originated from a manual input and might not be the same as those in the autopilot design IV&V'd by Analex-Cleveland. The Defense Contract Management Command (DCMC) software surveillance personnel were not aware that the I1 filter rate constants contained in the flight software were generated by a manual input, and were never tested by LMA in their pre-flight FAST simulation or IV&V'd by Analex. The LMA Software Quality Assurance staff, not understanding the manual input and single check for the I1 filter constants, left the I1 constant checking process to the LMA CD and flight software engineers.

b. The sub-process to create the constants database for the resulting flight tapes and firing tables was not well documented. The flight software engineer who creates the database dealt with over 700 flight constants generated by multiple sources, in differing formats, and at varying times (some with multiple iterations) all of which had to be merged into a single database. Some constant values came from electronic files that could be merged into the database, others from paper memos manually input into the database. Procedures for creating and updating the database were not formally documented and were left to the flight software engineer's discretion.

c. The lack of focus and understanding of Inertial Measurement System (IMS) software and operations, and Inertial Navigation Unit (INU) testing contributed to the poorly defined process for generation and test of the I1 rate filter constants. The INU, for which all of the flight software is developed, consists of two major software components developed by different companies. The LMA developed the Flight Control System (FCS) software and is responsible for overall INU testing. Honeywell developed the IMS and is partially responsible for its software development and testing. The I1 constants are processed by the IMS, but are designed and tested by LMA. The focus of the LMA flight software process is on FCS versus IMS software. Key players in the flight software development, test and mission/quality process (to include LMA control dynamics engineers, flight software engineers, product integrity engineers and software quality assurance personnel; Analex-Denver personnel; and DCMC personnel) focused their efforts on FCS operation and had little knowledge of IMS operations.

d. The process allowed single point failures for mission critical data. The manually input I1 filter rate values were only checked by one individual other than the individual actually inputting the data. The software engineer who manually inputs the I1 constants had no formal, documented process to check or verify his work. He did not catch his own error. The LMA CD engineer who designed the I1 rate filter did a manual visual check and sign-off of a set of numbers produced by the software engineer. Those numbers were contained in two paper documents with different decimal and exponential formats for the three values cross-checked for each I1 constant. The CD engineer did not catch the error. The constants verified in the Sign-off Report become the baseline for the flight tape and the "truth baseline" given to Analex-Denver for verification. The process did not require Analex-Denver to check the accuracy of the numbers in the "truth baseline," only to do a range check and a bit-to-bit comparison against the firing tables that also contained the incorrect constant. Once the incorrect filter constant went undetected in the Sign-off Report, there were no other formal checks in the process to ensure the I1 filter rate values used in flight matched the designed filter.

e. The consolidation of the major contracting companies responsible for Titan/Centaur development, and the evolution of the Titan/Centaur program into a mature system contributed to the splintering and poor understanding of the overall software development, test and quality/mission assurance process. The Centaur software process was developed early in the Titan/Centaur program. Many of the individuals who designed the original process are no longer involved in the process due to corporate mergers/restructuring (e.g. Lockheed, Martin Marietta, General Dynamics) and maturation/completion of the Titan IV design/development program. Much of the system and process history, and design rationale was lost with their departure. For example, the FAST test bed was designed so it could use the actual I1 roll rate filter constants; however, recognition of this capability was lost in the corporate consolidation/evolution process. As a result, the current software engineers performing FAST testing use a set of default roll rate filter constants. Had they used the actual flight values in their simulations prior to launch, they would have caught the error. The SMC Launch Programs Directorate had no permanently assigned civil service or military personnel to work Centaur software. Since Titan/Centaur software was believed to be mature, stable and relatively problem free, the Directorate felt it could best use its limited resources to address pressing hardware issues.

f. Analex developed (with LMA and government approval) an IV&V program that did not verify or validate the I1 filter rate constants actually used in flight. The Titan/Centaur "community" responsible for development of the IV&V program for the flight software, did not fully understand the overall process used for generating and testing the flight constants. Analex did not understand the generation or internal verification process for all the constants in the "truth baseline" they were given by LMA to verify. They did not know the I1 constants were manually input and manipulated, nor did they know there was only one person checking them in the LMA verification process. Consequently, they did not verify that the designed I1 filter constants were the ones actually used on the flight tape. The validation testing they performed also did not use the actual I1 constants contained on the flight tape. A set of generic or default I1 constants were used in their simulations since they believed the actual I1s could not be adequately validated in their rigid body simulations. They found out after the mission failure that had they used the actual I1 constants in their simulation, they would have found the order of magnitude error.

g. The fragmentation/stove-piping in the flight software development process, coupled with the lack of an overall defined process, resulted in poor and inadequate communication and interface among the many players and many sub-processes. Approximately one week before the Titan IV B-32 launch when the flight tape containing the actual roll rate filter constants was loaded at the launch site, LMA personnel at CCAS observed much lower roll filter rates than they expected. When they could not explain the differences at their level, they raised their concerns to Denver LMA guidance Product Integrity Engineer's (PIEs) who were now at CCAS. The on-site PIEs could not explain the differences either, so they directed the CCAS personnel to call the CD design engineers in Denver. Due to poor and indirect communications, (voice mail and e-mails) and lack of understanding of each other's responsibilities and processes, their concerns were not adequately addressed. The LMA personnel at Denver never asked to see the actual data observed at CCAS, nor did they talk to the engineer and data analyst at CCAS who questioned the low filter rates. There was confusion/uncertainty from the time the issue was raised until it was "resolved" as to how it should be reported, analyzed, documented and tracked since it was a "concern" and not a "deviation." If those issues had been adequately addressed, the mission failure could have been averted.

h. No formal processes existed to check validity of the I1 filter constants or to monitor attitude rates once the flight tape was actually loaded into the INU at CCAS prior to launch. No one other than the CD engineers who designed the I1 roll rate filter constants understood their use or the impact of filtering the roll rate to zero. During the day of launch when the tower was rolled back, data was collected that identified the pitch and yaw channels were responsive to environmental stresses (i.e. wind) but the roll channel was flat. At that point in the pre-launch process, no one was required to monitor or analyze the data. Consequently, no one was able to question the rate data or correlate it to the low roll rates observed about a week prior to launch. If someone who understood the I1 roll rate filter design had been monitoring the rate data, the error could have been detected and the mission failure averted. During the day of launch, the attitude rates for the vehicle on the launch pad were not properly sensing the earth's rotation rate. Again no one had the responsibility to specifically monitor that rate data or to perform a check to see if the attitude filters were properly sensing the earth's rotation rate. A simple root sum square plot of the sensed attitude rates would have identified the problem. The INU PIE did notice the low roll rates and performed a rate check to see if the gyros were operating properly. Unfortunately, the programmed rate check uses a default set of I1 constants to filter the measured rates, and consequently verified that the gyros were sensing the earth rate correctly. If the attitude rates were monitored at that time, or summed and plotted to ensure they were properly sensing the earth's gravitational rate, the roll rate problem could have been identified and the mission failure averted.

Quality/Mission Assurance

i. A software quality assurance function existed and operated at both LMA and DCMC but operated without a detailed understanding of the overall process or program. In addition, transition from an oversight role to an insight role was not implemented properly by either agency because of that lack of understanding. The DCMC personnel performing surveillance on the software development process did not have a clear understanding of the process when they developed their surveillance plan. They did not understand that manual input of the I1 constants caused a single point failure in the process, and consequently did not identify those areas as high risk in their surveillance plan. Their risk analysis was not based on determining steps critical to mission success, but rather on how often problems had previously surfaced on past launches. They determined constants generation was low risk since there had not been previous problems. They only checked whether the Sign-off Report containing the constants had all the proper signatures. The LMA Quality Assurance staff left the I1 constants generation and verification process to the involved LMA engineers, and limited their own involvement to verifications of checksums and placing quality assurance stamps on the media. The LMA Quality Assurance Plan is the original General Dynamics developed plan, recently updated only to comply with ISO 9001. It is top level and emphasizes verification of task completion rather than task implementation/execution. Few of the General Dynamics personnel who created the plan and understand the process remain with the Titan/Centaur program.

j. The Space and Missile Systems Center Launch Directorate, and the 3SLS have undergone personnel reductions and are transitioning from a task oversight to a process insight role. The Titan Program Office, which is part of the Directorate, had no full time organic support working Titan/Centaur software. They decided that since Titan/Centaur software was mature, stable and had not experienced problems in the past, they could best use their limited organic resources to provide insight into a myriad of hardware issues that they had with LMA. The Program Office did have support from Aerospace to monitor the software development and test process, although that support has been cut by over 50 percent since 1994. The Aerospace personnel were not aware of any problems with the I1(25) constant prior to launch, nor were they aware the flight I1 constants were never verified or validated in the Analex IV&V process. The 3SLS has greatly reduced the number of engineers working launch operations. There is no master surveillance plan in place to define tasks for the remaining staff who use their best engineering judgement to determine what tasks they should perform. Although there was a 3SLS engineer who saw the roll rate data at the time of the tower roll back, he was not able to identify the problem with the low roll rate. He had no documented requirement or procedures to review the data, and no reference with which to compare.

The Accident Investigation Board concludes that for the Titan IV B-32 mission, there is no question as to the mission failure mode or root cause. We believe both the failure mode and root cause are accurately and completely identified and described in this report.

J. GREGORY PAVLOVICH, Colonel, USAF
Accident Investigation Board President

Figure 7

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