THE GA'LILEO TAPE RECORDER REWIND OPERATION ANOMALY

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ABSTRACT

On October 10, 1 995, the Galileo spacecraft executed a sequence to record two approach images of Jupiter on the spacecraft's tape recorder, rewind the tape, and play back the images at the appropriate data rate consistent with the downlink performance The recording of the images was performed and the spacecraft computer commanded the tape recorder to rewind the tape to the beginning of the first image. The rewind command was started at the proper time but the tape never got to the beginning of the image data, The analyses and tests that followed allowed a conclusive determination of the failure mechanism and indicated a strategy that could be used to prevent the untimely demise of the mission.

1NTRODLJCTION

The Galileo spacecraft's mission is to drop a probe into the atmosphere of Jupiter and then tour the Jovian system for two years with an encounter of a moon every one to two months. The data will provide information on the system and the individual moons structure, composition, and environments. The spacecraft was launched from Kennedy Space Center aboard the Space Shuttle on October 18, 1989. Galileo's trajectory involved a gravity assist from Venus and two gravity assists from Earth. Galileo released its Jupiter atmospheric probe on July 13, 1995 for a ballistic trajectory to the giant planet. The spacecraft reached its destination at Jupiter on December 7, 1995 and the atmospheric probe entered Jupiter's atmosphere exactly as planned. The data from the probe was recorded on the spacecraft's digital data tape recorder and has all been returned to Earth for study, The spacecraft is currently approaching another moon for its next encounter and significant data return.

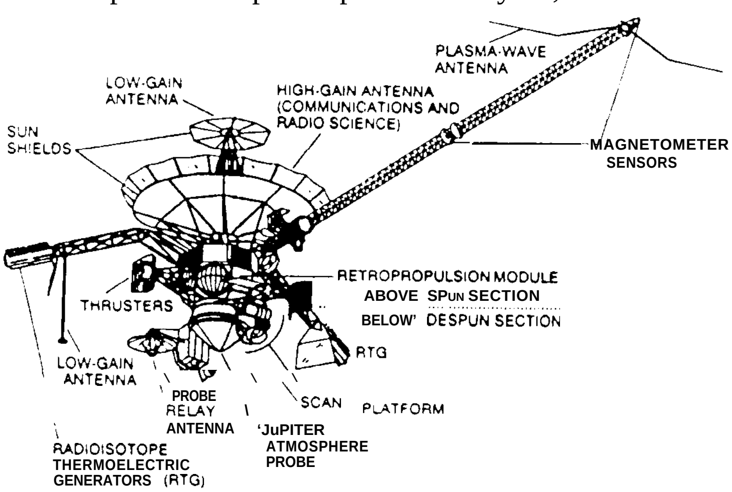


Figure 1.
Galileo Spacecraft Configuration

'l'he Galileo spacecraft (Figure 1) is a spin stabilized spacecraft with seven fields and particles instruments and four imaging instruments There are two antennas in the high gain antenna assembly, the high gain dish and a low gain planar antenna The second low gain antenna seen in the figure was only deployed for use during the first five years of the mission and is no longer usable for communications, The primary transmission source for returning the science data to Earth was designed to be the High Gain Antenna (l-IGA) which was capable of transmission rates up to 134 kilobits-per-second (kbps). Some of the science data rates from the instruments reach 806 kbps which is too high for the HGA. To handle this data rate and serve as a back-up for out of sight encounters, a tape recorder capable of record rates up to 806.4 kbps was incorporated into the spacecraft design. There are several operating modes for the tape recorder at different data rates from 7,6S kbps to 806.4 kbps. The different data rate modes include different combinations of the various science instruments. The lowest data rate for recording and playback on the tape recorder is 7.68 kbps and this mode does not include any imaging science. To obtain imaging science data the recorder must be operated at a higher data rate than 768 kbps.

On April 11, 1991, the Galileo spacecraft's High Gain Antenna failed to deploy properly which had serious mission implications[1]. The only remaining data downlink was the Low Gain Antenna (LGA). This antenna's downlink data rate performance was only 10 bps at Jupiter, With the slowest data rate from the instruments (no images) of 7,68 kbps, the data could not be sent over the LGA The solution to this problem seemed to be the tape recorder, The data from a single encounter could be recorded onto the recorder and played back slow enough that the LGA link could be used to return the data. The quantity of science data from a single encounter is enough to fill up all of the space on the tape. This approach has the limitation that a complete return of the data from a full tape recorder would take over three years. This time frame is inconsistent with the need to dump the entire recorder between each encounter: one to two months

From October, 1991 through February, 1992, a JPL team worked on developing options to solve the data return problem with the HGA unusable, The total strategy developed by this team consisted of adding compression, editing, and encoding software to the spacecraft and arraying the ground based Deep Space Network antennas to obtain a higher signal to noise ratio. The software added to the spacecraft was installed in the main computer as well as some of' the instruments' computers, Science data during an encounter will be recorded onto the tape recorder, played back from the recorder, modified, and sent through the LGA to Earth. This total strategy reduced the downlink time for a full tape from over three years to just around two months. The mission was possible again with the caveat that the tape recorder went from being a backup piece of hardware to a mission critical item.

The Rewind Anomaly and Telemetry Description

On October 11, 1995, the spacecraft recorded two approach images of Jupiter on the beginning of the tape and then attempted to rewind the tape for playback of the images, The telemetry from the spacecraft indicated that the tape never reached the beginning while the motor was running at the proper speed for several hours. The rewind operation should only have taken 26 seconds to complete. If the motor was running the wrong direction, the end of tape should have been reached within five minutes. At this time, Galileo was only two months from Jupiter arrival and the return of the atmospheric probe data. Since the atmospheric probe data was of the highest priority and the tape recorder was required for complete data return, the rewind anomaly had to be understood and a solution determined in time for the December 7 arrival at the giant planet.

There are four types of telemetry provided from the tape recorder, These four are:

1, Motor current
2. Tape position
3. Presence of servo lock
4. Beginning of tape/End of tape (BOT/EOT)

The motor current telemetry provides a Data Number (DN) that is proportional to the current drawn by the tape drive motor. Since the motor is a brushless dc type, the current is proportional to the torque load on the motor.

The tape recorder provides pulses, or tics, while its motor is running that are proportional to the length of tape passed through the drive mechanism. These are incremental tics from the tape recorder itself. The incremental tics are summed up in the spacecraft computer and a "tic count" number is generated for tape position telemetry. This telemetry should always be between 200 and 7183 representing the beginning and end of the tape, respectively.

When the tape drive mechanism is operating, it is very important that the speed of the tape be maintained accurately. The drive motor has a rotor encoder that provides speed data for the tape drive mechanism's servo control loop. When the recorder is operating in the slew or record modes, the encoder is used as the speed sensor and the control loop is closed around it. When the recorder is in the playback mode, the actual recorded data is used by the servo control loop to determine the tape speed. When the control loop has obtained a speed error signal within certain limits, a servo lock indicator in the recorder's telemetry changes state to indicate the servo "lock-up".

The ends of the tape in the recorder have clear sections that are sensed by a photoelectric device. This device outputs a hi-level signal indicating that the tape has reached the end of travel, The tape recorder has internal circuitry that detects the presence of an end of tape indicator. If an indicator is detected, the circuitry stops the tape drive immediately and reverses the tape direction if appropriate, The machine's internal circuitry will only accept commands that move the tape away from the end of travel. The presence of an end of tape indicator is provided through the recorder's telemetry outputs.

Figure 2 shows the motor current telemetry received during the rewind anomaly. The expected nominal motor current for the tape position and speed at the time was 160 DN which was right in the center of the data. This telemetry did not indicate that a problem had occurred. A stalled motor would saturate the current telemetry signal since its dynamic range is 255 DN (the equivalent stall value would be 738 DN). Figure 3 shows the tape position telemetry decrementing and then rolling over to the maximum value to continue decrementing. The large gaps correspond to missing groups of telemetry data. The rolling over of the count indicates that the data is going beyond the allowable limits for this telemetry. Using the tape position telemetry to determine the motor speed yields the result that the motor was running at exactly the commanded speed of 806.4 kbps. Since the rewind command uses a slew mode for the recorder, the servo lock telemetry as well as the tape speed are determined from the motor rotor encoder. The servo lock telemetry indicated that the motor was in lock to the commanded speed. The fourth telemetry, BOT/EOT, never indicated that either end of the tape had been reached.

TAPE RECORDER MECHANICAL DESIGN

The tape recorder used on the Galileo spacecraft is an Odetics, Incorporated Model 3100. This type of recorder uses AMPEX type 799 one-quarter inch wide tape, The tape is constructed of a polyethylene terephthalate base film (Mylar), gamma ferric oxide in a polyester urethane binder, and a backcoat of carbon black in a polyester urethane binder. The backcoat materials were selected to provide a good friction surface for driving the tape as well as a conductive surface to minimize the generation of static charge from the motion of the tape, The polyester urethane binder is produced from the combination of carboxylic acid and an alcohol. This process produces esters and water and the reaction is reversible, Since the reaction is reversible, there are always some unreacted components present in any sample of tape, corresponding to the equilibrium quantities for the temperature and humidity level within the tape. The generation of the alcohol and carboxylic acid is known as hydrolysis and these hydrolysis products are sticky (this is the technology behind the licking of a postage stamp to “activate” the adhesive). [2] in the 1960’s it was learned that all tape recorders had to be run in an atmosphere with a certain humidity level to prevent the generation of huge static discharges in the machine. The ideal humidity level was deter-mined to be between 30°/0 and 50% for the temperatures that tape recorders were operated.[3] This humidity level has a corresponding concentration of hydrolysis products within the tape. These products remain suspended in the tape and do not present a threat to proper operation of the recorder. Because of the Acquirement to maintain a certain level of humidity around the tape in a recorder, all Odetics recorders are sealed with a 30% to 40% relative humidity atmosphere of nitrogen and helium. [4]

Figure 2.
Motor Current Telemetry vs. Time

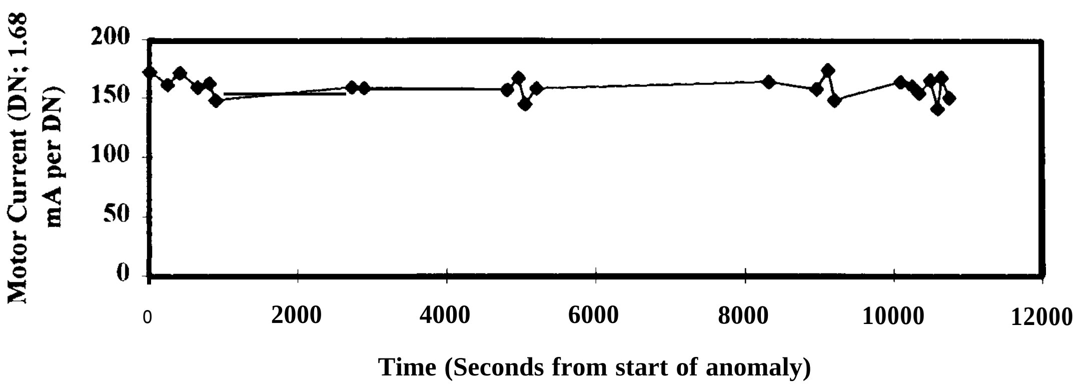
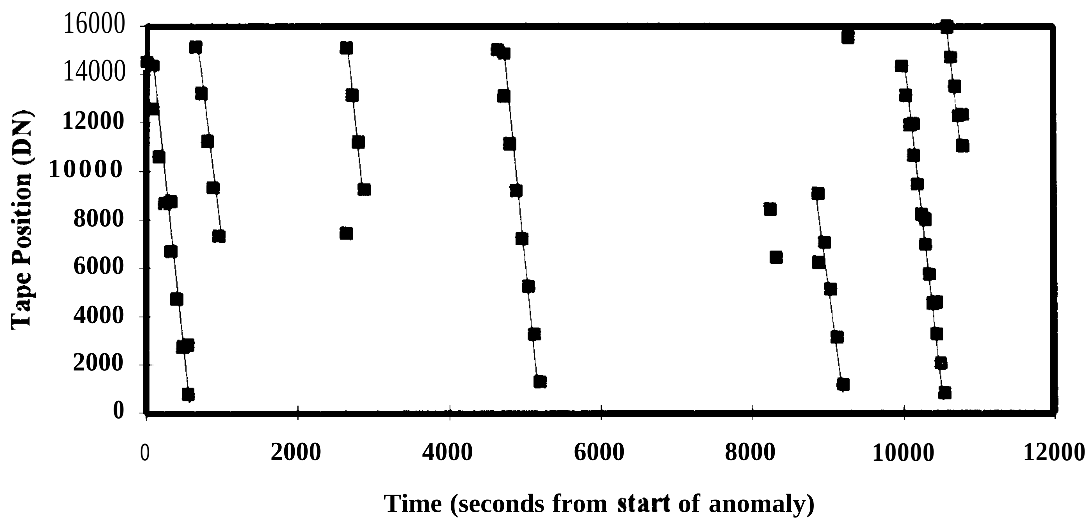


Figure 3.
Tape Position vs. Time



The tape is wound onto two reels that are stacked on top of each other and counter-rotate to minimize the uncompensated momentum that is injected into the spacecraft.

The tape is wound onto two reels that are stacked on top of each other that counter rotate to minimize the uncompensated momentum that is injected into the spacecraft. Figure 4 is an outline drawing of the tape path in the recorder. The circles with numbers in them represent rollers or capstans that control the tape [illegible] upper reel the tape exits and wraps around roller #1. The path then takes the tape through the "BOT Block" which houses the photoelectric sensors for detecting [he beginning of the tape Roller #2 is tilted relative to the axes of the reels and lowers the tape half of the distance to the lower reel. Rollers 3 and 5 guide the tape to the first capstan, #4. The tape then passes over a play back head, roller #6, and another playback head. The second capstan in the drive system is the apex capstan at location #7. The next two heads in the path are the record heads with roller #8 in between. The third and final capstan in the drive system is #10. Roller #9 performs the same function as roller #4 and maintains the [illegible] wrap angle around capstan # 10. Roller #11 positions the tape so it can be lowered the remaining distance to enter the lower reel by tilt roller #12. The tape then passes through the EOT block (same as the BOT block but detects the end of the tape), over the "dummy" erase head, around roller # 13, and onto the lower reel. From the tape entrance and exit angles on the reels, the counter rotation of the reels is evident. The tape is driven through the group of rollers and onto the reels by the three capstans 4, 7, and 10. The drive force to move the tape comes from friction between the backside of the tape and the capstans. For this drive technique to work properly there must be constant tension on the tape

The required tape tension is provided by a single negator spring operating on the two reels through a differential mechanism as shown in Figure 5. The reels are independently supported on the differential shaft by a preloaded pair of bearings for each reel. This allows the reels to move freely relative to the differential shaft and each other, The negator spring applies torque to the differential shaft. This torque is reacted through the spider gear to the reels which provides the tape tension needed for the friction drive system to work. Refer to Figure 4 to see how both ends of the tape are tensioned [illegible] single applied torque. The spring is always trying to pull the tape onto both reels. The capstan drive system pulls the tape off of one reel and the spring winds the tape up onto the other reel.

During any move of the tape, the reel speeds will not be the same; the reel that has more tape on it will rotate slower. The differential mechanism shaft rotation rate will be proportional to the difference of the two reel speeds. At the exact center of the tape where there is the same amount of tape on each reel, the reel speeds will be the same and the differential shaft will stop rotating. As the tape passes the exact center, the difference in rotation rates of the two reels will change sign since the reel with the most tape will have changed position (i.e. upper to lower reel). The result of this motion is the negator spring is unwound, stops, and then rewound as the tape goes from one end to the other. If the tape is released at any position, the spring system will drive the tape to the center of tape where the negator is fully unwound. The nominal motor current to move the tape from one end to the other is shown in figure 6 and is independent of the direction of tape motion. The monotonic nature of the current is due to the motor holding back the

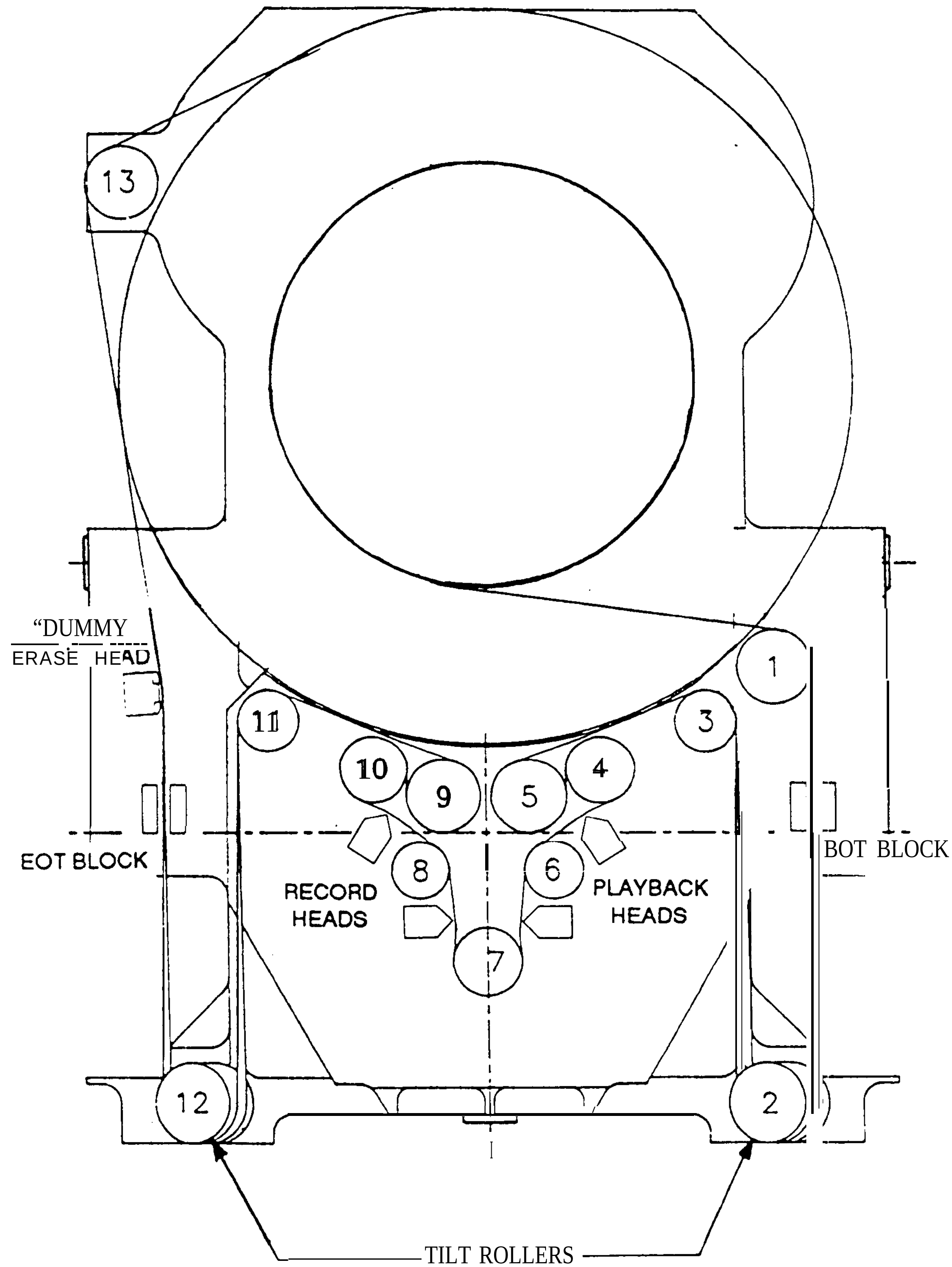


Figure 4.
Tape Path Outline

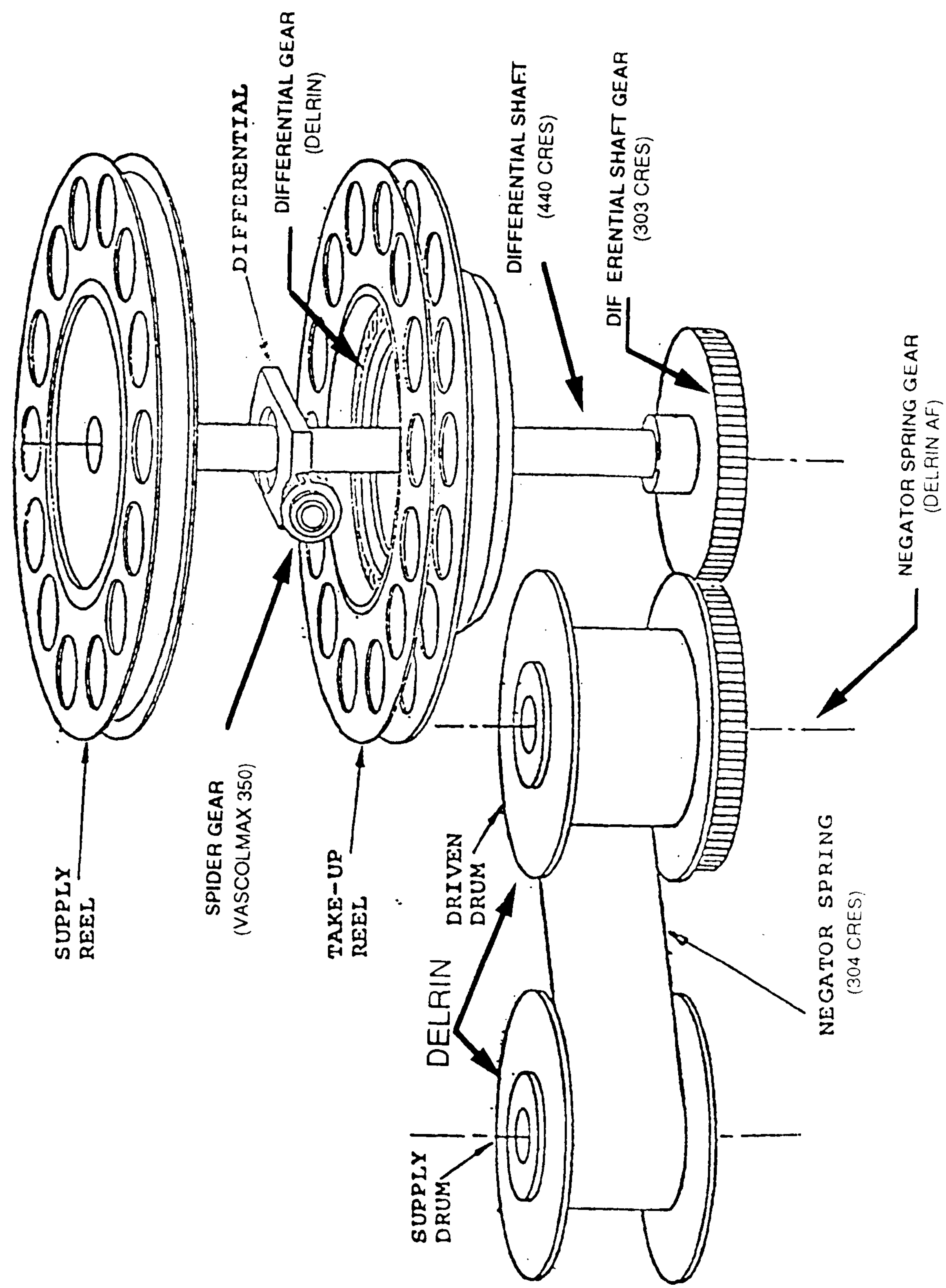


Figure 5.
Spring and Reel System

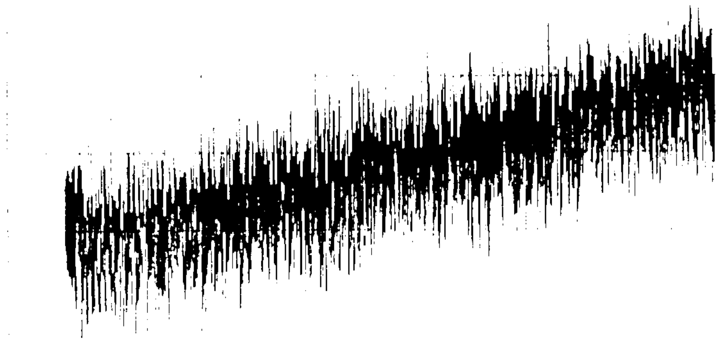


Figure 6.
Nominal Motor Current Trace at 7.68 kbps
1400 Feet of Tape, Reverse or Forward

negator (acting as a brake) as the center of tape is approached, and then rewinding the negator after passing the center of the tape, is current profile requires the knowledge of tape position to determine what the nominal motor current should be for a given operation.

The drive system for the three capstans is shown in Figure 7. The motor drives a central pulley that has three Kapton belts wrapped around in the configuration shown. This approach guarantees that all three capstans run at the same speed and does not introduce any drivetrain noise in the tape motion. The wrapping technique of the belts minimizes the radial load on the motor bearings providing for a longer life. The tachometer (encoder) wheel is connected directly to the motor rotor to maintain the highest speed accuracy during slew and record modes.

The tape recorder contains a total of 21 preloaded pairs of radial contact ball bearings. All of the bearings are mounted in housings and on shafts of the same material as the bearings (440C) to minimize changes in the drag torque due to thermal expansion. When the recorder was assembled the drag torque of the bearing pairs was measured and screened for applicability. Only assemblies with acceptable drag torque and ripple are used in the final mechanisms. All bearings are lubricated with EXXON ANDOK C. This grease is filtered to 10 microns absolute and applied to the bearings through a syringe. This technique is used to maintain a very accurate volume of grease and even distribution within the bearings.

The tape recorder contains a total of five heads. Two of the heads are for playback, two of the heads are for recording, and the fifth head is a dummy head. Many of the recorders that had a lot of' flight heritage prior to the Galileo build used a de erase head in this location, Since the surface of the head is also a tape guide, the dummy head was installed for the purpose of maintaining the tape path heritage. Figure 8 shows the

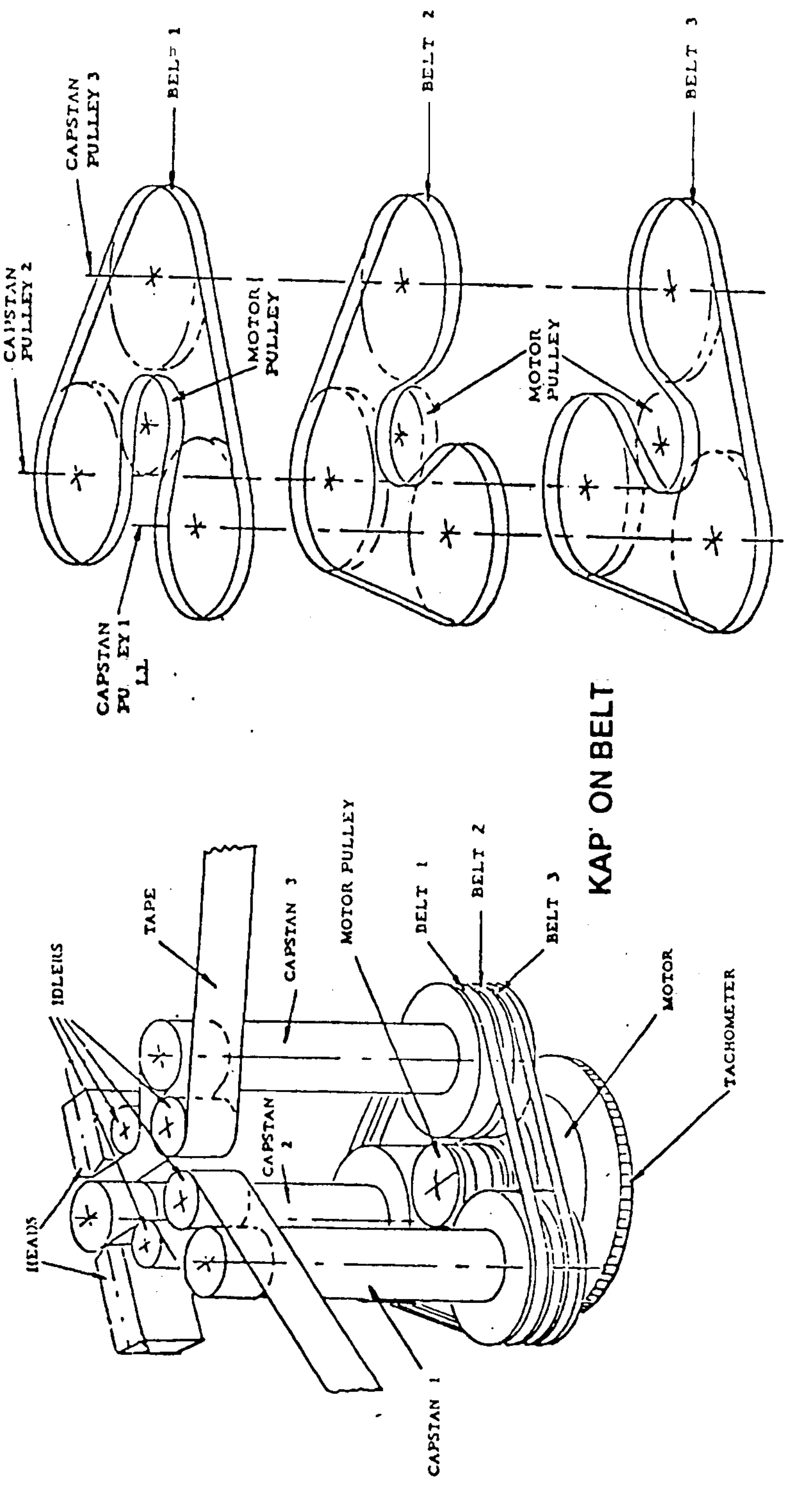


Figure 7.
Three Capstan Drive System

construction of the dummy erase head. The interface to the tape, the two sapphire rods, is the same as the previous machines from which the heritage was obtained. The four active heads are constructed of AlFeSil which is a standard recorder head material.

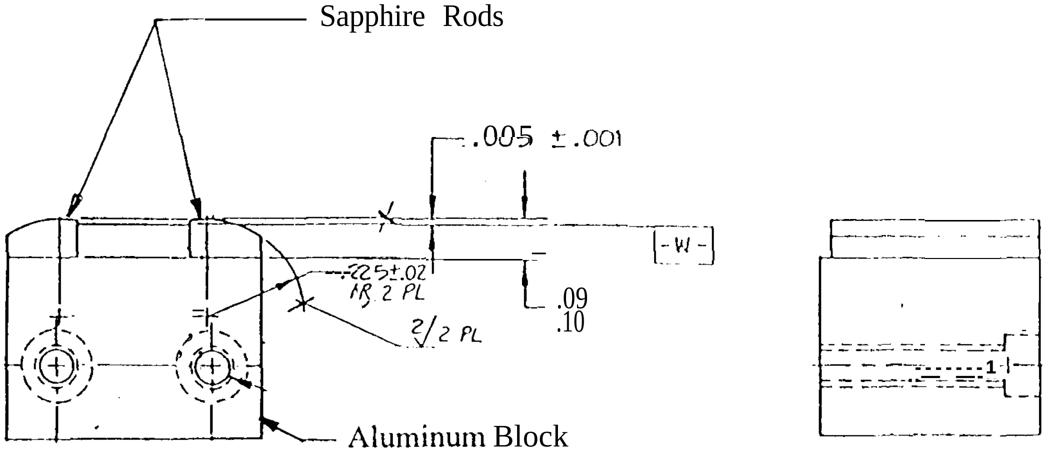


Figure 8.
Dummy Erase Head Construction

Failure Analysis

A complete study of the recorder mechanisms was performed following the anomaly on October 11, 1995. This effort produced a fault matrix that pointed to the following failure possibilities:

1. Tape slippage at the capstans
2. Tape sticking to the dummy erase head
3. Tape sticking to a roller on the BOT side of the drive

With this knowledge, the recorder could be operated in the forward direction and the data from this operation would provide more information on the possible failure. On October 20, 1995 a test was performed that moved the tape forward for ten seconds. The motor current from this test is shown in Figure 9 and showed a high startup current with all recorder status and operations nominal afterward. The tape position is recorded with the data on the tape and this information showed the tape never moved during the rewind anomaly. This indicated that the tape recorder was still usable and the capstans must have slipped on the backside of the tape. Since there was concern that the tape was structurally compromised where the capstans spun against it, the next motion of the tape

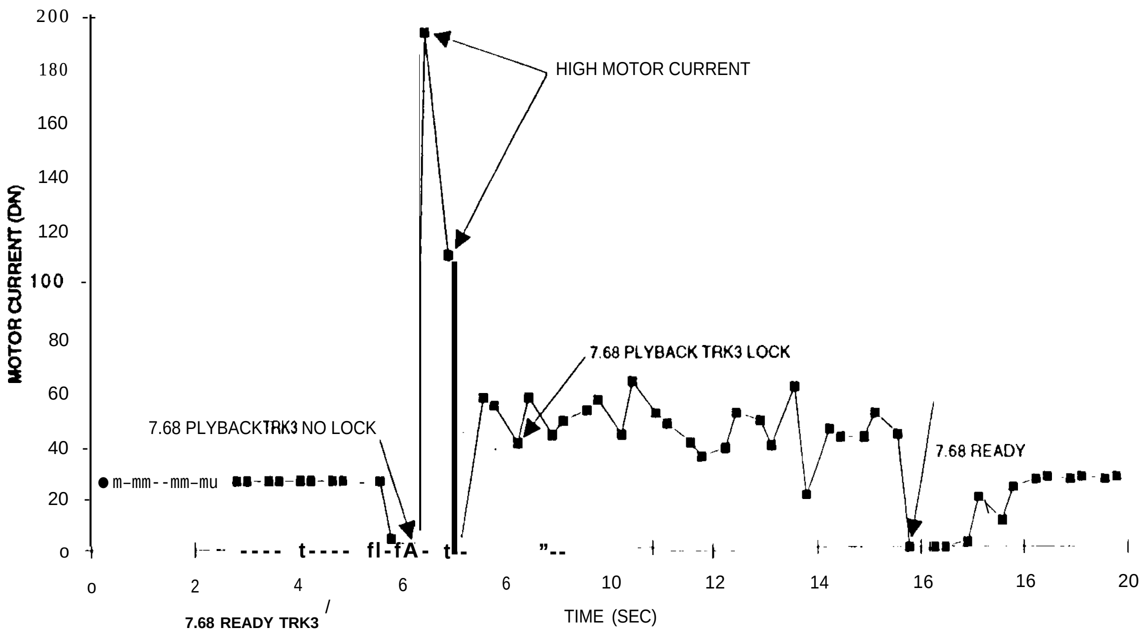


Figure 9.
Motor Current Telemetry
10/20/95 Spacecraft Recorder Test

recorder was to wrap the compromised section onto the reel. During this motion there was a drop in the servo lock signal indicating an out of lock condition. Since the move was done in the playback mode, this indicated that the data on the tape was damaged at the drop out point. Previous motions of the tape recorder were researched and two other cases of unexplained tape position error were found. The characteristics of each of the three failure situations are listed below (the preceding numbers are the year - day of year):

1. **95-284: 806.4** kbps rewind failure,
   - No leader indication after 15 hours at 806.4 kbps reverse slew.
   - Motor current not erratic.
   - No loss of servo lock.
   - Incremental tape position pulse rate consistent with commanded speed.
   - No motion of tape as determined by subsequent recorder operation.
   - Initial high motor current at startup of subsequent tape move.
   - Servo lock drop out after moving tape 20 inches from the anomaly position.
2. 95-186: 806.4 reverse rewind failure for 4.4 seconds near center of tape.
   - Tape position after completed rewind was 83 while the expected count was 191.
   - Only slip in reverse could account for this discrepancy since forward slip would produce an ending count higher than the expected value.

3. 95-258: 7.68 kbps reverse record failure near center of tape.

- Motor current 70 DN higher than expected for the first eleven minutes of a 22 minute move.
- After an 806,4 kbps slew to the end of the tape, the end was reached 155 tape position pulses earlier than expected,
- 155 pulses early is consistent with eleven minutes of tape slippage at 7.68 kbps.

Note that all of the failures occurred while the tape recorder was operating in the reverse direction. In January, 1996, a tape conditioning operation (consisting of winding the entire tape from one reel to the other) was performed that produced another (fourth) sticking failure with the following signature:

4. 96-019: 100.8 kbps forward playback to 7.68 kbps reverse playback.

- Motor cur-rent 80 DN higher than expected with servo in-lock at 100.8 kbps for-ward playback.
- **7.68** kbps reverse playback showed servo out of lock
- 7.68 kbps forward playback was then executed and showed an initial high motor current.
- 7,68 kbps reverse playback was executed again and showed nominal tape recorder operation.

The fault matrix was updated with the four failure signatures listed above incorporated 'I'his led to a single conclusion for the failure that could produce all of the failure signatures. This matrix is shown in Figure 10. The failure signatures are listed above each column and the failure scenarios are listed to the left of each row. The presence of an X indicates that the failure scenario could account for that particular signature. The total number of X's for each scenario are listed in the far right column Only the failure scenarios that have an X in all of the columns are candidates. The tape sticking to the dummy erase head is the only scenario that fits all of the signatures.

FAILURE MECHANISM

Once the failure scenario had been identified, the next question was how does the tape stick to the erase head and why don't all of the recorders built by Odetics have the same problem, A significant amount of testing was performed to answer these questions Several sticking mechanisms were investigated while a search for spare recorders of the same vintage took place, The result of the search yielded a Magellan spacecraft spare recorder that was built at the same time as the Galileo recorder and used the same lot of magnetic tape. This spare recorder was obtained and operated to see if it exhibited any of the sticking characteristics that the Galileo flight recorder had. After the first move to

ASSEMBLY	#	ITEM	95-284-06 · H²S REVERSE SLIP: 10s/103 OK	95-284-06: MOTOR CURR OK	95-284-06: SERVO IN LOCK SLEW REVERSE	95-284-06: TACH PULSES CORRECT	95-284-06: FOLLOWING FWD 7.68 HI INITIAL CURR	95-284-06: TOTOMIM 7.68 27.2SEC SERVO DROP	95-284-06: TAPE SLIP REVERSE TIC 833	95-284-06: STATUS OK ●806 SLEW REV	95-186: TAPE SLIP REVERSE 108 TICS (TIC 4413)	95-186: SERVOINLOCK SLEWREVERSE	95-186: STATUS OK 0506 SLEW REV	95-258: MOTOR CURR 700N HIGH 7.68 REV (TIC 4407)	95-258: TAPE SLIP REVERSE 155 TICS	95-258: SERVONLOCK RCDREVERSE	95-258: STATUS OK ●7.68 RCD REV	96-019: MOTOR CURR 800N HIGH 7.68 REV (TIC 7047)	96-019: FOLLOWING FWD 7.68 HI INITIAL CURR	96-019: SERVO OUT OF LOCK PLYBCK REV	96-019: STATUS OK ●7.68 PLYBCK REV	TOTAL
REEL ASSY	1	BEARINGS INCREASE DRAG	X		X	X			X	X		X	X			X	X			X	X	11
	2	SPRING NEGATOR BREAKS	X		X	X			X	X		X	X			X	X			X	X	11
	3	SHAFTS BREAK	X		X	X			X	X		X	X			X	X			X	X	11
	4	GEARS BREAK NEGATOR / SPIDER	X		X	X			X	X		X	X			X	X			X	X	11
	5	GEARS NEGATOR JAMS	X		X	X			X	X	X	X	X		X	X	X			X	X	13
	6	GEARS SPIDER JAMS	X		X	X			X	X	X	X	X		X	X	X			X	X	13
DELTA DRIVE		BEARINGS																				
	8	SHAFTS BREAK CAPSTAN	X		x	X			X	X		x	X			X	X			X	X	11
	9	SHAFTS BREAK MOTOR	X						X	X			X				X			X	X	7
	10	CAPSTAN SLEEVES SLIP ON TAPE	X	X	X	X			X	X	x	X	X		X	X	X			X	X	14
	11	CAPSTAN SLEEVES CRACK		X	X	X				X		X	X			X	X				X	9
	12	PULLEY BREAK	X		X	X			X	X		X	X			X	X			X	X	11
	13	PULLEY SHAFT DISENGAGEMENT	X		X	X			X	X		X	X			X	X			X	X	11
	14	BELTS KAPTON STRETCH	X		X	X			X	X	X	X	X		X	X	X			X	X	13
	15	BELTS KAPTON BREAKS	X		x	X			X	X		X	X			X				X	X	11
	[illegible]	MOTOR [illegible]																				[illegible]
TAPE PATH	[illegible]	[illegible]ARING[illegible] ROLLE[illegible]																				[illegible]
	18	TAPE BREAK			X	X			X			X				X				X		6
	19	TAPE STICK ON ACTIVE HEAD	X		X	X			X	X	X	X	X		X	X	X			X	X	13
	20	TAPE STICK ON "DUMMY" ERASE HEAD	X	X	X	X	X	X X	X	X	X	X	X	x	X	X	X	X	X	X	X	16
	21	TAPE STICK ON ROLLERS	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	16
	22	TAPE STICK ON CAPSTAN	X				X		X	X			X				X		X	X	X	9
	23	TAPE STICK IN REEL PACK	X		X	X			X	X	X	X	X		X	X	X			X	X	13
	24	SHAFTS BREAK ROLLERS			X	X			X	X	X	X	X			X	X			X	X	11
	25	TAPE SLIP ROLLERS	X	X	X	X				X		X	X			X	X				X	9
	26	ROLLER SLEEVES CRACK		X	X	X				X		X	X			X	X				X	9
STRUCTURE	27	HOUSING LEAK	PRE X — URE XDUCER SHOWS NO SIGNS OF LEAK																			N/A
	28	STRUCTURE WARP	X		X	X			X	X		X	X			X	x			X	X	11

Figure 10.
Tape Recorder Mechanical Fault Matrix

the end of the tape the Magellan recorder stuck with the same signature as the Galileo flight recorder.

After the Magellan recorder became stuck, it was carefully opened and inspected. The tape had stuck at the erase head (the Magellan units used the dc erase head function and had an active head at this position with the same sapphire rod interface) and there was a visible film of brown residue on the head. The head was then removed for inspection of the debris. The debris was chemically analyzed for composition and found to be composed solely of magnetic tape constituents. A diagram of the debris on the head is shown in Figure 11. Note that the debris is located on both sapphire rods yet appears to be interleaved (as if the debris from one rod broke off and was transferred to the other rod). This investigation found that the sticky stuff is in fact the normal tape debris generated by the passing of tape over the erase head.

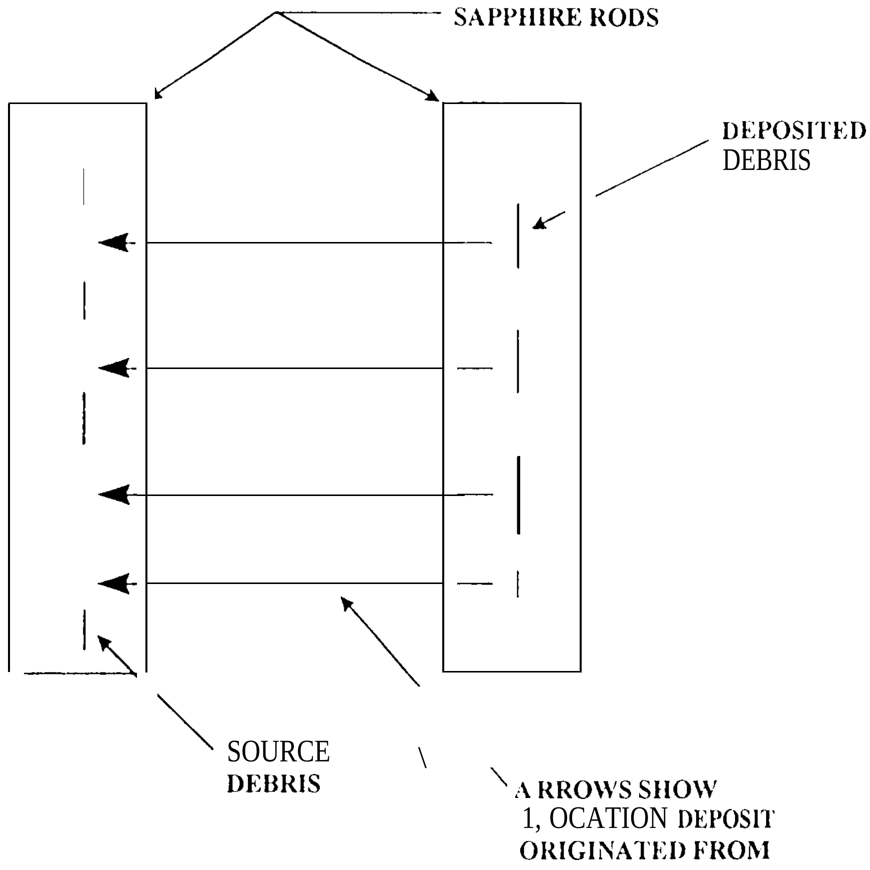


Figure 11.
Magellan Recorder Erase Head
Debris Distribution

The best model identified to date for depositing tape constituents on the erase head maintains that the generation of debris from running tape over the erase head is a natural process that occurs with new tape. New tape is naturally abrasive and "wears in" during the first operation of the machine. 'he sapphire rods on the erase head promote a high tape wear rate (compared to the AlFeSil active heads) as observed in laboratory tests This wear-in process creates the tape debris as well as wears flat spots on the sapphire rods, A large portion of the tape debris is swept up by the tape into its pores, After a sufficient amount of tape is passed over the head, the wear rate drops to essentially zero. This was verified by taking a worn-in tape and running it through a machine with a new sapphire head for two million feet, The result was that no discernible tape debris was generated. However, when a new tape is installed with a new head, the tape produces visible amounts of debris in less than two thousand feet of travel.

This information led to the development of a debris model that is consistent with all of the data uncovered to date. The required order of events that lead to a sticking recorder are as follows:

1. New tape is installed and operated in the machine. This process wears the tape and erase head sapphire rods, producing debris.
2. Once the tape recorder meets its performance requirements (but prior to completion of the debris generation phase), the machine is thoroughly cleaned by Odetics prior to sealing the unit for flight
3. The tape machine is sealed with the appropriate atmosphere inside.
4. The tape continues to generate significant amounts of debris until its high wear cycle is complete.
5. This generated debris is collected outside of the tape-to-head contact area, presenting no threat to recorder operation.
6. At some point in flight, a portion of the debris beaks off of the collection area and is swept by the tape into the tape-to-head contact area on the opposite rod
7. The debris caught in the contact area is worn by the moving tape causing an intimate contact area with a resultant stick,
8. The tape is broken free from the head by operating the recorder, This severs the debris leaving some debris stuck to the tape and some debris left behind in the contact area.
9. The debris left in the contact area acts as a gathering agent and collects more debris from the tape.
10. Steps 7 through 9 repeat.

The tape debris collected at the head is currently believed to contain a high concentration of hydrolysis products. This would explain the sticky behavior of the material. Two tests have been performed to verify this hypothesis. The first consisted of applying a solution of hydrolysis products to the erase head and operating the tape recorder to see if the sticking performance matched the observed behavior on the flight unit. The second test involved putting a reel of unused tape from the same lot as the

Galileo flight tape onto the recorder. This tape has hydrolysis products on the entire oxide surface as deter-mined by chemical analysis. The recorder was then operated to produce the sticking condition. The results from both of these tests showed that the sticking behavior of the tape matched the flight unit for a time. Eventually, the sticking phenomenon disappeared because all of the debris deposited on the erase head was removed. This result is consistent with what was seen on the Magellan flight spare unit. When the tape was pulled off of the head, the debris was sheared, removing some of the debris from the head. If this process continues every time the tape is torn from the head, the quantity of debris available to cause the tape to stick will continue to reduce to the point where the tape no longer sticks.

To answer the second question of why don't all of the Odetics tape recorders stick, the entire operational history of three units was investigated The three units were

1. The Galileo flight unit on the spacecraft
2. The spare Galileo flight unit located on the ground
3. The spare Magellan flight unit located on the ground

The spare Galileo unit was built at the same time as the unit on the spacecraft and has never shown any evidence of the tape sticking. The assembly and testing history suggests that the difference between the units that stick and others that don't is the amount of tape passes put on the machine prior to the final cleaning and closing of the unit, This is consistent with the stick model because the units that stick had not completed their high wear cycle and so continued to produce debris in significant quantities after the units were sealed. On other units, the debris generation had dropped to the nearly imperceptible level prior to final cleaning at Odetics and no longer produced enough debris to cause the sticking phenomenon throughout their entire life.

GALILEO TAPE RECORDER OPERA'I'1OX STRATEGY

All of the testing that has been performed with several sticking tape recorders has shown that the magnitude of the stick does not exceed the ability of the motor to break the tape free by operating the recorder in the forward direction. The limiting factor in the ability to release the tape from the erase head is the drive motor stall torque. The stall torque can produce about 32 ounces of tension in the tape at the erase head. This tension is not enough to break the tape but is about 30% greater than the strongest stick measured during all of the ground testing.

The stick model (step 7 above) requires the debris on the head to be worn in order to obtain an intimate contact area with the tape, This implies the need to run a minimum distance of tape over the head before a stick condition exists, The data from the flight recorder indicates that this is the case. If the recorder is only moved a short distance, the tape will not stick to the erase head and there is no danger in moving the tape in the reverse direction. The current Galileo strategy is to always move the tape recorder in the forward direction for a short distance prior to any motion in the reverse direction. To date this strategy has proved acceptable since the spacecraft has had five encounters consisting of over twenty reverse operations of the tape recorder per encounter with no detectable slipping of the drive. Any slipping events would be detected by the tape position telemetry not being consistent with the expected position.

CONCLUSIONS

The Galileo flight tape recorder is critical to the completion of the spacecraft's mission to study the Jovian system of moons and the giant planet. The rewind anomaly that occurred on October 11, 1995 seriously threatened the mission's data return, After exhaustive review of the tape recorder design it was determined that the recorder could be operated and the tape was sticking to the erase head in the machine. The cause of the tape sticking to the head was traced back to the tape itself and the natural generation of debris. The current model indicates that the bulk of the tape debris is generated during the early operation and testing of the recorder. This high debris generation at the start of the recorder's life coincides with the maximum tape and head wear period. The major factor that determines the potential for tape sticking in a particular recorder is where in the tape/head wear cycle the erase head was cleaned prior to flight. Testing also indicates that the wear rate of the sapphire rods used as "rubbing surfaces" on the erase head is significantly greater than the AlFeSil material used in the other four heads. This characteristic results in the tape debris deposition occurring mostly at the erase head. The continued production of debris inside a closed and sealed recorder could then lead to a sticking condition at the erase head. Once a machine has set up a sticking condition the recorder must be operated in a certain way to prevent tape slippage. All tests indicate that several sticking events can remove the debris from the erase head until the tape no longer sticks to the head, This means that the possibility of the Galileo flight recorder problem healing itself exists, leading to a recorder that operates normally in the future

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