Telemetry Analysis

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Some of the ways in which Soviet missile flights and the missiles themselves can be reconstructed by monitoring their signals.

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A ballistic missile stands on the launch pad poised for a test flight. As the countdown nears zero, its rocket engines light up, the umbilical cable linking it to the launch pad is cut, and the "bird" lifts off to begin its trip into space. From the moment the umbilical cable falls away, the missile's designers must rely on telemetry (measurements of key variables converted into electrical signals and radioed to ground stations) for their observation of the performance of its components.

While the missile is in flight these multi-channel telemetry signals are received at ground stations along the trajectory and relayed back to the control center, where the measurements are displayed, usually in the form of line traces, one for each channel, on long strips of paper. Anxious engineers cluster about a set of these "analog records" to get a first quick look. Along with the records, the instrumentation specialists provide a key to the assignment of the telemetry channels so as to identify which trace is recording which kind of measurement and a list of calibrations, conversion factors for translating a given trace deflection into so many units of pressure, temperature, flow rate, or other variable.

All this must be done by any missile launch facility, whether it be the U.S. Atlantic or Pacific missile range or the Soviet sites at Tyuratam or Kapustin Yar. Thus when we intercept Soviet telemetry we may be able to use it to measure the performance of Soviet missiles. There are two very serious handicaps, however; first, the intercept usually covers only the time when the missile is above the horizon of the place of interception, and second, we have neither a key to the channel assignments nor a list of calibrations. The analyst can do little about the first handicap; this is a problem for the collectors. How we seek to overcome the second one and the kinds of information we get when we succeed are described below.

Which is Which?

In trying to identify the various Soviet measurements, we make use first of all of the fact that certain basic measurements are required on any flight, regardless of what additional specialized ones may be called for. For instance, the propulsion system will always have a measurement of acceleration and one of thrust chamber pressure; and if the engine is liquid-fueled, with gas-driven turbopumps feeding the propellants in, then we are likely to see pairs of measurements of the pressures at the inlet and outlet of the pumps for both fuel and oxidizer and readings of gas generator pressure, turbine speed, and fuel and oxidizer flow rates. A liquid propellant missile stage with the common instrumentation on the propulsion and propellant feed systems is pictured schematically in Figure 1. We thus know what to look for and can search the Soviet telemetry for counterparts of readings on U.S. missile flights.

If a tentative identification is made, we can then apply various tests, based on the laws of physics and on reasonable design practice, to check its validity. A trace suspected of being an acceleration measurement, for example, we check against the theoretical plot of acceleration against time for a constant-thrust missile, a hyperbola governed by the equation: a (Kl-t) = K2, where a = acceleration, t = time, and K1, K2 = constants.

If the identification of acceleration is validated, the next step derives from the fact that the force producing the acceleration, the thrust of the rocket, is proportional to the pressure in the thrust chamber. If minor perturbations in the acceleration record, therefore, correlate very closely with some in another trace that does not have the hyperbolic characteristic, this second trace becomes a fair candidate for the thrust chamber pressure.

From here on, the analysis gets more complex as we delve deeper into the system; but there is usually a reasonable expectation that, so long as a good sample of telemetry is available, it will be possible to identify all the major measurements. Of key importance here is that the sample include a major transition period such as engine shutdown. In a liquid-fueled turbo pump-fed engine, for example, the fact that the pressures in the propellant feed system drop to zero at shutoff in considerably less than a second while the turbine, rotating at high speed with a great deal of inertia, takes 4 to 8 seconds to coast to a stop is most useful for identification purposes.

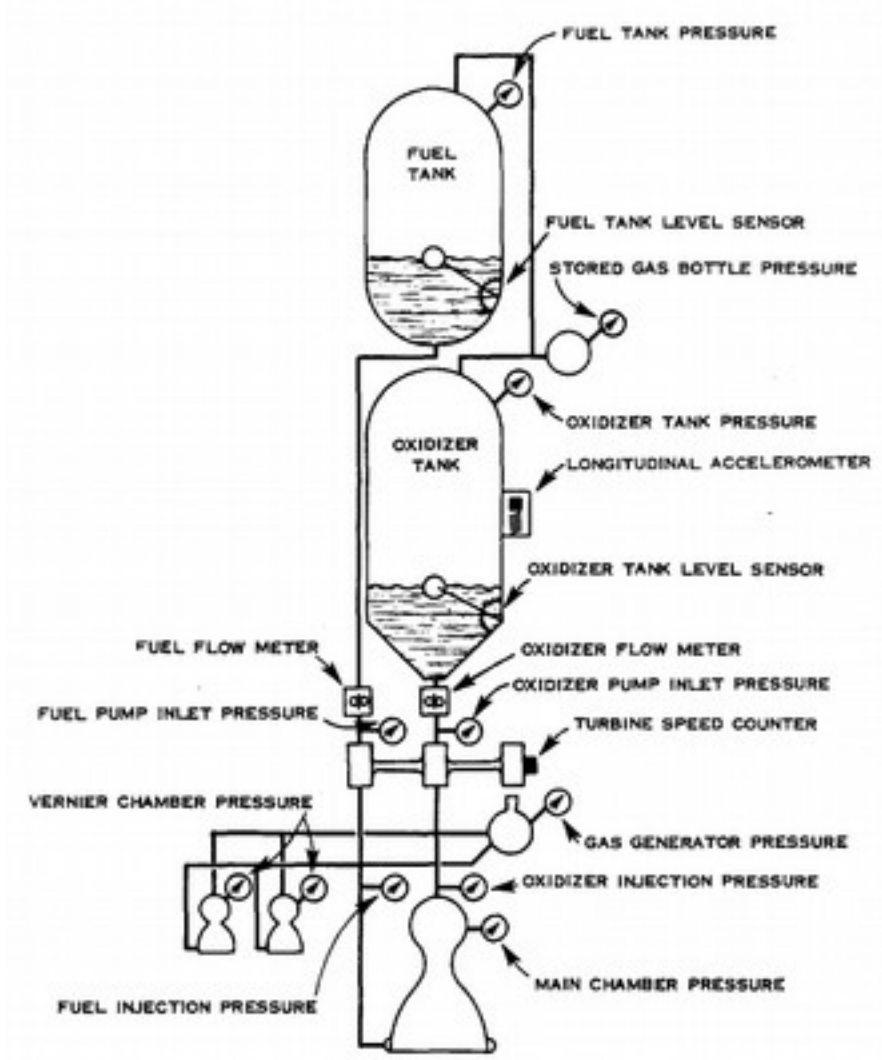


FIGURE 1. Typical Missile Stage Instrumentation.

Merely to have made a few of the key identifications brings a considerable intelligence benefit, because we can then relate the firing under study to earlier ones and form an opinion on whether it is one of a series or is testing a new vehicle or possibly a new model of a known missile. Given a fair sample of powered-flight telemetry, the analyst can usually say whether the vehicle is liquid- or solid-fueled, whether it has a single burning stage or multiple stages, and what ratio of payload to total weight it probably has.

Acceleration

The single most important measurement and the one most useful in the analysis is the acceleration of the missile along its longitudinal axis. Every so often we intercept the signal before first-stage burnout, and the trace looks like the example shown in Figure 2 (but without any annotations except time). From this record we would_ know immediately that the missile had two main burning stages of which the first shut down at 100 seconds, that it then coasted for five seconds until the second stage ignited, and that this burned for an additional 145 seconds to shutdown. The low plateau in the record after second-stage shutdown would tell us that small vernier rocket engines (for fine regulation of burnout velocity) operated for 10 seconds after main-engine cutoff, and the ratio of this acceleration to that at main-engine cutoff would be the ratio of vernier engine thrust to total thrust. The short negative displacement at 270 seconds signals the firing of retrorockets to separate the rocket body from the payload.

Note in the same figure the dotted line starting at second-stage burnout and continuing the hyperbolic curve that would reach infinity at 308 seconds. This is a theoretical extension of the acceleration, showing how it would rise if the missile had continued burning and losing weight at the normal rate of fuel consumption, so that when the weight dropped to zero the acceleration would become infinite. The significance of this is that it gives us an upper bound on the payload weight in the form of a ratio between the weight of the vehicle at burnout (payload plus empty rocket stage) and the weight of the propellants burned by the stage, these two weights being proportional respectively to the time from burnout to infinite acceleration and the time from firing to burnout. Then, if through some additional analysis it becomes possible to introduce an actual weight into the equation, an estimate can be made of the ratio of empty stage weight alone (largely tankage) to propellant weight, the stage can be sized, and the payload can be determined. This process can now be repeated for the first stage, so that the complete weight history of the vehicle from liftoff to burnout becomes known.

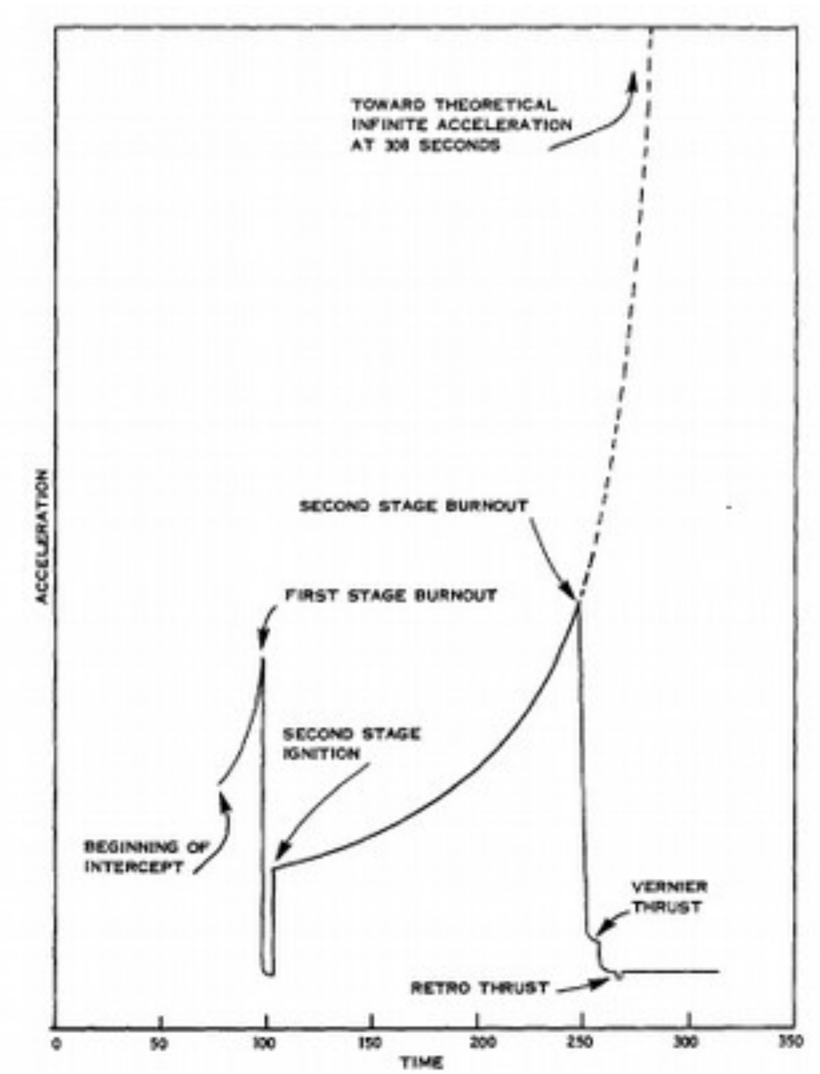


FIGURE 2. Typical Missile Acceleration History.

Vibrations and Transition Times

Another approach of telemetry analysis, one which probably holds the most promise for determination of missile size, is the examination of time-related functions such as vibrations and pressure transients. Telemetry traces identified as measurements of liquid level in the propellant tanks have occasionally showed a rather slow oscillation of low magnitude. This usually is indicative of wave action at the liquid surface, or sloshing. Now the interesting thing is that the rate of these oscillations, which can be measured directly from the traces, is dependent only on the diameter of the tank, the acceleration of the missile, and the shape of the tank bottom. Further, if the phenomenon occurs when the liquid is more than a tank diameter away from the bottom, then the shape of the bottom has no effect either, and we need to know only the acceleration to get a measurement of the diameter of the tank.

Analysts have also noted an oscillation of higher frequency superimposed on measurements of pump inlet pressures. Because a conventional missile will have its tanks in line, feeding the propellant from the upper tank to the engine requires a long pipe passing through or around the lower tank. It has been found that in U.S. missiles this pipe acts somewhat like an organ pipe: the longer it is, the lower the frequency, or pitch, at which it will vibrate. The phenomenon enables us to get the length of the pipe by measuring the frequency and comparing it with that from known missiles, and this pipe length is essentially equal to the length of the lower propellant tank.

Another occasional observation, one that seems promising but has not yet proved productive, is that the entire missile vibrates at a frequency which gradually changes as the burning proceeds and makes a step change when the nose cone is separated at burnout. This is as it should be, because the vibration frequency is related to the stiffness of the missile, which is in turn a function of the length, diameter, weight, and construction materials. Thus while the propellants are burning the missile weight and stiffness are changing continuously, but when the nose cone is separated the weight and length change instantaneously, producing the step change in stiffness. Very little intelligence has so far been derived from this type of analysis, however. The ballistic missile cannot be treated as a simple hollow cylinder; its complex structure has to be considered in detail.

The study of transient phenomena is another area which gives promise of providing intelligence. Very recently it has been shown that for a wide variety of U.S. rocket engines the time it takes for the chamber pressure to fall at cutoff from its operating level to near zero seems to vary directly with the size, i.e., thrust, of the engine. The relationship seems to hold for engines using different propellants and operating at different chamber pressures. Furthermore, it seems to hold for Soviet engines as well; those whose thrusts have been estimated by other methods show pressure decay times that fall right on the curve described by the U.S. data. The precision with which we can read out the thrust is quite poor, but the method does give us a rough cut at the size of the engine in a new missile, discriminating between, say, a Saturn-size engine and a Titan-size one.

Liquid Level Measurements

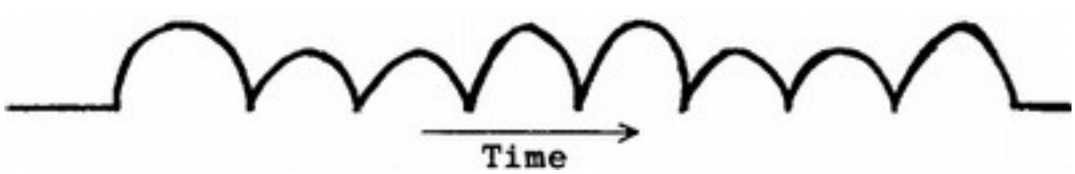
A third approach which has been very useful is analysis of telemetered data on liquid levels. So far all the major Soviet ballistic missiles have used liquid propellants, and they are often equipped with instrumentation for measuring how full the tanks are. The sensors are usually installed in both the fuel and oxidizer tanks, and they allow us to monitor the efficiency of propellant utilization. Ideally, one wants a missile to reach burnout with an excess of neither fuel nor oxidizer, and bow closely this ideal is approached is a measure of the effectiveness of the system.

Information on the shapes of propellant tanks can be gained from the level sensors. When the liquid is up in the main cylindrical portion of the tank the rate of drop in level will be constant, but as soon as the level enters the tank bottom it will start dropping at a faster rate, and the precise way it falls with time will be a result of the geometry of the tank bottom-conical, elliptical, spherical, or some other shape. Thus if we have a good record of the changing liquid level near burnout we may be able to determine the shape of the bottom. This is not just an interesting academic exercise, because if we know the geometry of the bottom along with the time needed to empty first the cylindrical part of the tank and then the bottom, we can calculate the ratio of length to diameter and exert some leverage on the sizing problem. Another important product of liquid level analysis is measurement of the volumetric ratio of oxidizer to fuel. If, for instance, the level sensors show twice as fast a drop in one tank as in the other, and if we make the reasonable assumption that the two have the same diameter, then we know that two volumes of one propellant are burned for a single volume of the other. We would therefore know that nitric acid is more likely to be the oxidizer than liquid oxygen, because oxygen burns efficiently with the common fuels at volumetric ratios lower than 1.6:1, whereas a 2:1 ratio would yield efficient combustion for a nitric acid system. This kind of information, when supplemented by other data such as specific impulse (thrust per unit of propellant flow rate) allows one to narrow the choice of propellant combinations significantly.

Calibration

Up to this point we have been talking mostly about measurements in the form of ratios, because it has been very difficult to determine absolute magnitudes. Two notable successes in calibration have been achieved, however-with liquid level sensors and accelerometers. These are described below.

The level sensor which has been calibrated is of the "hump" type, so called because its trace looks like this:



The calibration became possible when tank length for the vehicle was determined by an independent method. The total burning time was known, as well as the time it took for the instrument to cycle through eight humps. Then the ratio of these two times could simply be multiplied by the tank length to give the drop in level represented by the cycle. Having the calibration, we could now obviously turn it around and use it to measure tank length on any other Soviet missile which might use the instrument.

Acceleration traces have been calibrated by two techniques. The first is quite complex, requiring the history of the missile's acceleration and velocity to be reconstructed from its powered flight trajectory (usually with the help of a digital computer) by utilizing known or estimated data such as probable launch location, staging and burnout times, burnout position and velocity, ratio of acceleration at staging to acceleration at burnout, pitch program, drag coefficient, and the ratio of thrust in a vacuum to sea-level thrust.

The second technique, much simpler, can seldom be employed because it requires an intercept of telemetry before lift-off. Such intercepts are obtained only rarely because at launch the missile is always below the horizon of our intercept sites; we receive on-pad telemetry only when special atmospheric conditions cause the signals to be ducted along the earth's surface. If we do receive such a signal, and if an accelerometer is registering, then it will be reading one "g" (the accelerometer measures gravitational effect rather than acceleration proper) and by comparing this to its reading when the missile is under power we can calculate the acceleration at any time.

Whichever method is used, if the accelerometer is calibrated then we can go back to the equation for acceleration presented earlier, a (KI-t) =K2, and determine the magnitude of the constants KI and K2. Now KI is the initial weight of the missile stage divided by the flow rate, while K2 is the specific impulse, the thrust of the missile divided by the flow rate. Taking the last term first, the specific impulse is a figure of merit for a rocket engine reflecting principally the chemical energy available in the propellant combination, and it will be different for different propellants. Further, if we have (from liquid level sensor analysis) an idea of the ratio in which the propellants are mixed, we can make a pretty good stab at identifying the propellants. Then if by other methods we have sized the propellant tanks, we can now calculate the propellant flow rate, which multiplied by the constants KI and K2 gives respectively the initial weight of the missile stage and its thrust.

It is hoped that these explanations will have given the reader a better understanding of some of the mysteries of telemetry analysis and its usefulness in acquiring missile intelligence. Perhaps he will also appreciate more the fascination it holds for its devotees. One should note here the cumulative effect of a successful analysis: one breakthrough leads to another, that to another, and so on. Conversely, an erroneous conclusion will propagate errors, and in this respect this intelligence endeavor is probable no different from any other.

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