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An Area Correlator and a Photosensitive Crystal

It is exciting to contemplate the possible applications of a combination of these two highly precise yet relatively simple and inexpensive devices.

(*Abstract on next page*)

The True Area Correlator What Is It?

The Bolsey Associates Inc.† (BAI) True Area Correlator (BAI-TAC) is a device that has the unique ability of examining an area of the real world, or a photograph of the real world, and from this examination establish an electronic analog which uniquely defines the image it has examined. At some later date the BAI-TAC can search for, find, and lock on to that same image. If the original examination was made on a photograph, the BAI-TAC can find the corresponding area in the real world and vice versa. After finding the area which has been memorized, the BAI-TAC can then provide orientation information so that a vehicle or an instrument on a vehicle can be oriented with respect to the memorized area in accordance with a predetermined plan.

We call the device a *True Area Correlator* because it is the only one that we know of that truly examines the area *instantaneously* and then develops a unique electronic analog that *defines the area as an area.* This contrasts with the more common technique which examines the area point-by-point, and from this point-by-point examination tries to determine some means of defining the entire area.

How Does It Work?

The BAI-TAC is composed of two units, the sensor and the correlator.

The Sensor Unit

The sensor unit is much like a camera:

- The format can be quite large, just as a camera, but for most applications we prefer a format of between 16 mm. and 70 mm. in size.
- The angle of acceptance can vary from a few minutes of arc to a super-wide angle of 120 degrees or more.
- The focal length can vary from a few millimeters to 24 inches or longer.
- The aperture can vary from an $f/64$ to about an $f/1.2$.
- The exposure time can vary, but it is normally quite fast, in milliseconds.
- The cycling rate can vary, but it is also fast, in milliseconds.

With these characteristics one might envision a high performance 70-mm aerial camera or a 35-mm. recording camera. If one had made this assumption, he would not be too far wrong, because it functions much as if it is an aerial camera and a recording camera combined into one. One normally think of aerial cameras being used in the day, and with illuminants at night. Recording cameras are normally used to record radar

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* See also the preceding article "The BAI Image Correlator."—*Editor.*
† Now the BAI Corporation.

and infrared. A question might be, is he implying that the BAI-TAC can operate as an IR or radar sensor? The answer is yes. It can be used for day, night, adverse weather, and all-weather operations.

The sensor also has characteristics that differ from a camera:

- ★ The apparent focal plane, or platen rotates, and the usable format is round.
- ★ The aperture is determined by the width of the slit that exposes the annulus.
- ★ The sensor continuously scans, each rotation corresponds to an individual exposure.
- ★ The resultant image is not meaningful to the eye.
- ★ The image is processed in near real time, in milliseconds.
- ★ The image can be stored indefinitely or transmitted by wire or radio. It can be transmitted over any voice radio in 1/10 of a second. This characteristic makes the BAI-TAC a most versatile device, as will be explained later.

ABSTRACT: *Bolsey Associates Inc. has developed a True Area Correlator which has become one of the most precise and versatile instruments of its kind today. It measured and corrected for motion (x, y, rotation) in the Lunar Oribter to an accuracy of one second of arc. In the laboratory it can automatically reorient its longitudinal axis to one micrometer. It can operate in the visual, the infrared, or the radar parts of the spectrum. It has correlated side-looking radar even where the recordings were made at 180 degrees from one another. It can update itself every 5 to 10 milliseconds. Carson Laboratories Inc. has developed a potassium bromide crystal that could revolutionize the storage of continuous tone imagery, including color, and could completely change some end items such as maps and charts for navigation and flight control. The crystal resolution and tonal range is molecular, and is limited only by the recording and reproduction lens.*

THE RECORDED IMAGE

The BAI Annulus Signature (BANSIG) is an electro-magnetic recording which represents the variants in contrast along the annulus of the subject which the sensor is viewing.

THE CORRELATOR UNIT

In a block diagram the BAI correlator unit does not seem to be different from any standard correlator. Two signals are compared, each is compared with a delayed version of the other. Thus, comparing two signals, A and B, we form A-delayed and B-delayed and actually make a comparison between A and B-delayed and B and A-delayed. The results of this comparison are further compared to provide the actual correlation signal. One of the major differences between the BAI-TAC and other correlators is the detail of the instrumentation. The *resolution* of the BAI-TAC *is much much greater* than that of any other correlator that we know of, and this coupled with a very large dynamic range gives the system a *large pull-in range* and a *very high ultimate accuracy* without requiring that we make use of the common, fairly awkward techniques of changing the low lines, matching the video by-pass, etc., to allow the system to go from the pull-in mode of operation to its lock-on and track-type of operation. These abilities, coupled with the unique scanning and memory arrangement, make the BAI-TAC capable of performing functions which no other correlator we know of can perform.

HISTORY OF DEVELOPMENT

BAI has always envisioned that the development of the BAI-TAC would be made in three phases and in the following order: first an optical BAI-TAC for day operations; second, an infrared BAI-TAC for day-night operations; and third, a radar BAI-TAC for day, night, and all-weather operations. This development has followed pretty much as we had envisioned. The optical BAI-TAC was first started in 1959 and was used to demonstrate terminal guidance. The second application was in the photographic area. The Lunar Orbiter is the best example. We are at the present time preparing to deliver an infrared BAI-TAC to the Air Force for day-night operations. BAI has worked with GE radar engineers and has determined that the radar BAI-TAC is entirely feasible and could be demonstrated within about six months.

SENSITIVITY RANGE

The BAI-TAC needs only contrast. A blank piece of typing paper is sufficient. If one records the BANSIG at a time when it is illuminated by 2,000 foot-lamberts of light, he can acquire the same area on the typing paper when the light has been reduced to less than 20 foot-lamberts. We were all surprised to learn that we could record the BANSIG from any one of the nine exposures of the Itek Multiband Spectral camera and acquire the same area in any other. Eight of the exposures represent imagery in eight different narrow-band portions of the spectrum. The ninth exposure is the full sensitivity range of infrared film. The contrast in some pictures appear to be reversed, as the spectral range varies from 0.35 to 5.0 microns.

How Accurate Is It?

When operating in the Laboratory, the BAI-TAC has an accuracy in sensitivity of 1/2 a micrometer (μm)* or better. One will have a large error if he includes the effects of variations in vehicle performance, and other types of interferences which reduce accuracy and sensitivity. However, all these errors are random, so the RMS error will be about 1 μm. The angular accuracy of the BAI-TAC and lens combination is a function of the focal length of the lens and the inherent accuracy at the image plane. If we consider the BAI-TAC having a 1 μm (40 microinch) accuracy and use a 3-inch lens, the overall accuracy of the BAI-TAC as an error sensing device is approximately 0.1 minute (6 seconds of arc). Or putting it another way, .02 milliradians or 20 microradians. If a BAI-TAC is incorporated in a sensor which is used to point an instrument or close a servo loop, the errors of the associated equipment for closing the loop will introduce additional errors. As the combination of the BAI-TAC to this total error is quite small, the entire sensor can be made much more accurate by improving the performance of the components used in the rest of the loop. Improved high-gain amplifiers, high-precision gear trains (or elimination of the gear trains by the use of torque motors) can produce a system in which the accuracy of the entire sensor is approaching that of the BAI-TAC itself.

Acquisition Latitudes

Heading of the Vehicle

The heading of the vehicle introduces a rotation between the memorized scene and the scene of the real world. The 1959 BAI-TAC was extremely simple, but it could recognize a scene and lock-on if the heading had changed as much as ± 8 degrees. This can be improved by mechanically moving the optics or with a relatively simple *Search Aide* type circuitry, and then the area can be approached from any heading.

VIEWING ANGLE

Under experimental conditions the BAI-TAC can easily acquire a target which had been memorized from vertical photography when the viewing angle is changed as much as ± 45 degrees.

SCALE CHANGES

The simple 1959 BAI-TAC can accept changes in scale from 0.7 to 1.5 times the original scale. Thus, if the memorized information had been generated from an altitude of 10,000 feet, the BAI-TAC would recognize and acquire the memorized area at altitudes from 7,000 to 15,000 feet. BAI has designed several practical approaches which can be used to meet almost any requirement.

How Has It Been used?

The first BAI-TAC, as I mentioned, was started in 1959. It was completed in 1960 and demonstrated the ability to stay locked on to a converging moving image. Since 1960 several million dollars has been spent to reduce the size, weight, and power consumption. We have worked with Eastman Kodak, Lockheed, Martin-Orlando, Philco, and North American Aviation-Columbus to instrument the BAI-TAC for several applications as described below.

ACQUISITION AND TERMINAL GUIDANCE

In 1964 the original equipment was modified to increase the angle of acceptance from 2 degrees to 20 degrees, and the capacity to store 5 images instead of one. To demonstrate, vertical photographs were taken over a large, very realistic, three-dimensional terrain model, just as if you had flown an aerial reconnaissance mission over the real world. In fact, the model was so realistic that one would be hard pressed to tell that he had not flown from the Rockies in Colorado on to the Salt Flats of Utah. The BAI-TAC was then aligned with five selected areas on the photographs and the BANSIGs electronically stored for each. Over-flight was simulated at approximately 30,000 feet. The optical axis of the BAI-TAC was tilted 60 degrees forward of vertical and mechanically moved from side to side as the simulated aircraft moved forward. This permitted the BAI-TAC to acquire any stored target within a 17-degree cone below the vehicle. Four of the five BANSIG's could be of check-points over which one wanted to fly en route to the target. The fifth

* The micrometer (μm) is the successor to the micron (μ).

would be the target which would be acquired and terminal guidance accomplished. Hundreds of realistic flights were demonstrated.

IMAGE MOTION COMPENSATION (IMC)

Several BAI-TACs were instrumented to perform image motion compensation (IMC), but it all came to a climax with Lunar Orbiter I on 10 August 1966. When the Orbiter spacecraft approached an area to be photographed, the BAI-TAC was the first thing to be activated. It looked at the lunar surface and determined if it was necessary to correct for crab to align the cameras properly to the line of flight. Because the cameras were in a fixed installation, the whole spacecraft had to be rotated. The spacecraft is much like a big ship, once it begins to move, it is nearly impossible to stop it quickly, so this maneuver was performed very slowly. When the spacecraft got within one degree of being properly aligned, the BAI-TAC told the system to start taking pictures. The BAI-TAC then physically moved the platen, to which the film was attached, at the precise rate to compensate for the forward motion of the spacecraft. Then it signaled the shutters to click so that there was precisely the desired forward overlap between pictures. Finally, after all the film had been exposed, the BAI-TAC transmitted velocity-height ratio (V/H) signals to earth where they were recorded.

From another source accurate velocity signals were recorded. By feeding these V/H signals and the velocity signals into an adequate computer, height or altitude was determined. This is one of the ways used to determine the size and shape of the moon.

So, in the Lunar Orbiter the BAI-TAC was used to perform four functions. First, it was a drift meter. Second, it performed image motion compensation. Third, it became an intervelometer. And finally, it performed as an altimeter. In performing these functions, the BAI-TAC was measuring motion to one second of arc.

Automatic exposure control is inherent in the BAI-TAC and was considered, but dropped at the last minute.

How Can it be Used?

FLIGHT CONTROL

The BAI-TAC can be used in many ways to provide flight control. One of the simplest is to choose a flight path that would cross known checkpoints which have been selected from reconnaissance information. A more elegant application is one to control flight lines for making mosaics. On the first flight line the BAI-TAC looks out the side and generates a series of checkpoints, which are effectively in the adjacent flight line, obtaining checkpoints to indicate the exact path that has to be followed on the second line. Under these circumstances, the minimum required overlap, with no holidays, can be assured. It is often said that existing navigation systems are completely adequate for this operation. This is not always true. A good example would be to fly east and west across Honshu, Japan. You would go from the coast up over the mountains and down to the coast on the other side. If your barometric altitude was constant, which is normal practice, the ground area covered in the first exposure would be considerably greater than the area covered in the exposure made at the highest point over the mountains. In order to get the same sidelap between pictures the first line would be straight, and this is no problem for any navigational system, but then the aircraft would have to change course between every exposure on every line flown after that. I do not know of a navigation system that has been instrumented to perform such an operation. *This is a real simple task for the* BAI-TAC.

SENSOR CONTROL

It may be desirable to aim an airborne sensor at a particular spot on the terrain that the vehicle overflies. An example is to photograph a spot to saturation level. This requires that the sensor starts as soon as the area is within range and continues during the entire time that the vehicle is within sensor range. The BAI-TAC is uniquely designed to control any sensor to perform this function.

Conventional sensors. I do not anticipate that the conventional sensors used today will be modified internally to incorporate the BAI-TAC. We are convinced, however, that the BAI-TAC could be mounted externally to these sensors to control them, and the results would be considerably improved. The sensors could be maintained in a more precise and proper orientation to the ground. The exposures would be made at precisely the correct instant, and an automatic exposure control could improve photographic quality. If the BANSIGs were recorded at the instant of exposure, they could be used in several different ways at some later date, i.e., reflights due to cloud cover, or reflights on a periodic basis, where it is desirable to have exactly the same area covered in each exposure as was photographed on the previous flight.

Strip sensors. We think serious consideration should be given to the development of strip type cameras for mapping and charting. A simple BAI-TAC can solve all the problems that have made strip photography undesirable. We visualize that the BAI-TAC be mounted internally and share the same lens as the film. The camera would stay in precisely the same orientation with the ground. The film would move at correct rate. The exposure would be automatically corrected and, if desired, the focal length could continuously change to maintain the same scale along the center of the strip. Or, if more appropriate, the BAI-TAC could be instrumented to continuously record altitude, and or automatically focus the camera. The BAI-TAC controls are so precise that the resolution would be limited only by the film-lens combination. We think this camera would be ideal for flying a strip around the periphery of a rather large area that has already been photographed for mapping. The map would be adjusted to the periphery strip recording. Or, the strip camera could be used to fly down the overlapping area between two flight lines. In this case, the strip recording would be used as supplemental photography.

Multisensors for day, night, and all-weather. If the features of the BAI-TAC were optimized, multisensor recordings could be automatically oriented one to the other. I can visualize maps with ten or more overlays. They might aid federal, state, or city planners, or the geologist, or the civil engineer, or the mining engineer, and many others. Such things as air and water pollution and flood and crop controls are becoming more important all the time. If flight and sensor controls become automatic, these planners are going to insist on periodic coverage. This coverage may be as often as every three months. This nearly automatic mapping and charting flight control system could become operational within about two years.

GROUND APPLICATIONS

Use of conventional sensor recordings. Even if the BAI-TAC was not optimized for airborne applications, the BANSIG recorded in the air could be used with the BAI-TAC on the ground to automatically compile a map. The BAI-TAC can automatically recognize and establish passpoints. This means that long-line analytical computations could be made much faster and probably with greater consistent accuracy, especially where the image has little contrast, or where individual points are difficult to recognize. Other applications will make the eyeballs unnecessary for the operation of an orthophotoscope.

Unique sensor recordings. If the BAI-TAC was optimized for airborne applications, all ground uses would become less complicated. Equipment would be less expensive, much faster, and more consistently accurate. In fact, some useful end products might take a completely different form. An example might be an airborne mapping system with optical sensors, there could be several, which would cover 3/8 of the area of the side-looking radar. If one obtained 25 percent sidelap between lines with the optical sensors, he would obtain total stereo radar coverage of the same area obtained from adjacent flight lines.

SUPPORT OF TACTICAL WARFARE

Strategic air support. In this case, I am thinking of targets that are known but for some reason have not been hit. It is only necessary, then, to furnish the destructive weapon system with information so that it can navigate to that precise point in space where it must release its weapon to make it most effective. It sounds easy, but unfortunately the weather conditions, the time of day, the type of delivery systems that are available, and the type of weapons that it can deliver most effectively can vary drastically. We believe that if the BAI-TAC was in the weapon system, its effectiveness would be greatly enhanced. If optimized, one could have an all-weather capability. Also, if optimized, mapping or charting systems would have covered the area and the target could be destroyed with an automatic system. However, I am quite certain that for some time to come, man is going to take the systems off the ground and land them, and I would not be surprised if the pilot made a few fine adjustments en route. He may even have to take over and complete the mission as is done today. But one thing is for sure, the BAI-TAC can recognize some targets that man cannot, and when it does, its accuracy is far above the ability of a man. Probably one of the most significant advantages is that it would relieve a crew member of intense concentration during critical periods so that they can perform the overall task better.

Tactical air support. The BAI-TAC can only do one thing—it can always, except under extremely abnormal conditions, recognize an area that it has seen before, but it cannot recognize that something like a movable target has left the area. So, to use the BAI-TAC effectively, one must hit the target before it moves, otherwise one hits the spot where it just was, and it would never know the difference. There are several modes of operation:

- Where air survival is no problem, and rather deep air penetrations are made, the mission can be performed with the destructive weapon system alone. It can obtain the BANSIG on the first pass and hit the target on the second.
- Where air survival is a problem, and the possibility of making a second pass is near impossible. In this instance the BANSIG would be obtained from the first aircraft and transmitted to a Buddy-Boy that follows, and he would hit the target.
- Close air support of ground operations could be performed in much the same way—a low-flying spotting aircraft could obtain the BANSIG and then transmit it to the destructive weapon system flying above.
- A most intriguing application is where a ground unit is tied down by enemy fire. The exact position of the enemy could be determined by triangulation and plotted on the appropriate photograph. Even though the enemy was hidden by foliage and could not be seen from above a two pound, hand-held, BAI-TAC could be used to obtain the BANSIG on the tree tops, which have more than enough contrast to very accurately correlate. The BANSIG could then be transmitted to the destructive weapon system flying above and used to acquire and destroy the target below the trees.

Tactical ground support:

- ★ A ground commander could be self-supporting by using his own airborne vehicles as mentioned above.
- ★ If the BAI-TAC was optimized for an air and ground reconnaissance and surveillance system a very accurate photo-mosaic could be obtained in less than two hours. This would permit the precise position of his troops by having the field units record a BANSIG from his position on his photo-mosaic and transmit it to the control center where another BAI-TAC would search for and find that same position on a copy of the same photo-mosaic. Remember, it takes only 0.1 second to transmit a BANSIG over a land line or any voice radio.
- ★ These maps would be sufficiently accurate to use for firing surface to surface weapons. Slight errors could be adjusted by transmitting BANSIGs from forward troops on the ground or from aircraft flying above.
- ★ Another interesting application—a light weight, back-packed, infrared BAI-TAC could be instrumented to detect intruders automatically and continuously on the ground and determine precisely their position. Weapons could be automatically fired to hit the intruder or intruders.

Navigation and control. With appropriate flight charts, all flying vehicles equipped with a simple, light, relatively inexpensive BAI-TAC could be monitored and/or controlled, because one could continuously plot their precise position. Simple manned vehicles could, with only a PDI, perform unbelievably precise low- and high-level navigational feasts. Unmanned vehicles could do the same with the addition of an autopilot. With only slightly more sophistication mass flights could be accomplished with continuous flight control and precise distance separation control. Airport flight control could be accomplished from an airborne transport aircraft or a mobile vehicle on the ground.

Size, Weight, and Power Requirements

A simple hand-held BAI-TAC would weigh no more than 7 pounds. The sensor unit would be approximately 3×5 inches and weigh about 2 pounds. The correlator unit with battery power would be approximately $2\times4\times4$ inches and weigh about 5 pounds. This BAI-TAC would use no more than 10 watts of electrical power. The most sophisticated instrumentation would weigh no more than 25 pounds, occupy no more than 1 cubic foot, and use no more than 20 watts of electrical power.

Reliability

All equipment has better than a 2,000 hour MTBF (mean time before failure).

Cost and Time to Deliver

Cost has been quoted from $1,000.00 and up, per system, depending upon the application and the quantity.

THE SINGLE PHOTOSENSITIVE CRYSTAL

In 1955 an Air Force-Wide Reconnaissance Symposium was held at Maxwell AFB, Alabama. One speaker made a presentation on the subject of "A Systematic Approach to Strategic Reconnaissance." Of all the speakers, this was the only one to receive a standing ovation. I am sure that all those 200-odd people agreed that there was great logic to his approach to this problem. In short, he believed that if one could store complete radar coverage of an operational area in an aircraft, and if he could accurately relate the real-time radar imagery during overflight to that which was stored, he could deliver air weapons with great precision.

The technique of navigating to the target area, recognizing the IP, and maneuvering to the weapon release point are being improved every day, but the concept envisioned by this man in 1955 has not yet been demonstrated.

To accomplish this end, one approach might be to replace all conventional land maps, charts, and target material with one or several photosensitive crystals.

Carson Laboratories of Bristol, Conn., has developed a potassium bromide (KBr) crystal which has a tremendous storage capacity. It has sufficient capacity to store any type of imagery of an area covering at least 1,000 miles×1,000 miles on a single 2×2-inch crystal. This means that with a correlator such as the BAI-TAC, one could continuously determine his precise position any place at any time in this entire area.

The most important crystal would be the one containing complete radar coverage, but I think that it would be desirable to have two additional crystals—one with IR imagery and another with conventional map information. All three crystals could be synchronized and moved with the real-time radar, or an IR sensor if you did not want to radiate, or with the bomb-navigation system.

Any line-scan sensor imagery can be painted on one of these crystals in real time and projected continuously on a cockpit display without any processing. So, if one had both radar and IR sensors, together with two additional crystals, he could continuously view two live sensors and three stored crystals in any combination he chose. In fact, each of these could be projected in different colors, which would help to discriminate between sensors and aid in recognition.

An orthophotographic-type of crystal might be most useful for some operations. This would give one the same picture details as if he looked down at the real world, or looked through an optical or TV viewing device.

I visualize that the Aeronautical Chart and Information Center (ACIC) would eventually reduce the quantity of printed maps and charts for air navigation and be producing these crystals to replace them. It seems logical that the ACIC would also produce the radar and infrared or orthophotographic crystals in that they all should be at the same scale.

Sometimes I think we do not realize how rapidly new developments are overtaking us. There seems to be no end to the wonders of the laser. Carson Labs. has demonstrated how the laser can be used to keep the pilots head out of the cockpit. Imagine one seeing all his flight instruments and his gunsight reticle on his transparent windscreen. No gunsights or gun-cameras need obstruct his view.

If we are talking about the production of maps and charts for air navigation it should not surprise anyone if I said that, like the steam engine, the printing press will gradually fade away, but it will be replaced by something far more efficient.

Probably the question will be that in order to accomplish this, we will need to correlate and measure to micrometers. How can this be done on a production basis? I can only say that if the Toyota automobile manufacturing company in Japan measures cams on their camshafts to 1.25 micrometers, it would not seem unreasonable to expect that one can measure to 1 μm for map compilation. Also, if we can continuously measure 1 second of arc while in orbit around the moon, we can also do it for map compilation. The final question is, how can we automatically establish passpoints to 1 μm? Bolsey Associates Inc. of Glenbrook, Conn. has a contract with the U. S. Geological Survey to instrument the Lunar Orbiter BAI-TAC to demonstrate this capability. Carson Laboratories has a contract with the Navy to demonstrate the crystal application for multicolor cockpit map display. Hence, this total capability is just around the corner.

So, I say that the BAI-TAC and a KBr crystal can change things drastically.