[4] "Program assessment report, statement of findings. SPS concept development and evaluation program," Rep. DOE/ER-0085, Nov. 1980.
[5] W. J. Robinson, "Wireless power transmission in a space environment," *J. Microwave Power*, vol. 5, Dec. 1970.
[6] R. M. Dickinson and W. C. Brown, "Radiated microwave power transmission system efficiency measurements," Tech. Memo 33-727 Jet Prop. Lab., Cal. Inst. Tech., Mar. 15, 1975.
[7] G. Goubau, "Microwave power transmission from an orbiting solar power station," *J. Microwave Power*, vol. 5, no. 4, pp. 223–231, Dec. 1970.
[8] W. C. Brown, "Experiments in the transportation of energy by microwave beam," in *IEEE Int. Conv. Rec.*, vol. XII, pt. 2, pp. 8–17, 1964.
[9] R. M. Dickinson, "Evaluation of a microwave high-power reception -conversion array for wireless power transmission," Tech. Memo 33-741, Jet Propulsion Lab., Cal. Inst. Tech., Sept. 1, 1975.
[10] W. C. Brown, "Electrical and mechanical improvement of the receiving terminal of a free-space microwave power transmission system," Raytheon Contractor Rep. PT-4964 NASA CR-135194, Aug. 1977.
[11] W. C. Brown, "Satellite power system (SPS) magnetron tube assessment study," Contract NAS8-33157 NASA Contractor Rep. 3383, Feb. 1981.
[12] W. C. Brown, "Microwave beamed power technology improvements," Final Report JPL Contract 955104, Raytheon Report PT-5613, May 15, 1980.
[13] "Solar power satellite microwave power transmission and reception," NASA Conf. Publication 2141, pp. 219–220.
[14] W. H. Kohl, *Handbook of materials and techniques for vacuum devices*. Reinhold, 1967, pp. 487–491.

**William C. Brown** (A'39–M'55–SM'58–F'59) manages microwave power transmission system and device technology within the Microwave and Power Tube Division of Raytheon Company. He has made many contributions to microwave generator and rectenna technology, and has pioneered microwave power transmission systems including the first use of power transmitted by microwave beam to support a flying vehicle. He was a member of the first team to evaluate the technical and economic feasibility of the SPS (Solar Power Satellite) and has continued to contribute to the development of the SPS Concept.

# SAW Oscillators in UHF Transit Satellite Links

BINNEG Y. LAO, NEAL J. SCHNEIER, DAVID A. ROWE, ROBERT E. DIETTERLE, MEMBER, IEEE, JEFFREY S. SCHOENWALD, MEMBER, IEEE, EDWARD J. STAPLES, MEMBER, IEEE, and JACK WISE, MEMBER, IEEE

***Abstract*—A 375-MHz surface-acoustic-wave (SAW) resonator controlled oscillator was developed for application in the Transit satellite marine navigation system. The SAW oscillator, in a 2-in$^3$ hybrid package, contains a heater, voltage regulator, and divider and is a direct replacement for a bulk wave oscillator and its multiplier chain. A short term stability of $2E-10$ and an aging rate of $3E-8$/day were achieved at 75°C. Comparison tests showed that the accuracy of the navigation system with the SAW oscillator was equivalent to the accuracy using the bulk oscillator.**

Manuscript recieved April 13, 1981; revised August 4, 1981.
B.Y. Lao, N.J. Schneier, D.A. Rowe, and R.E. Dietterle are with Magnavox Advanced Products and System Company, Torrance, CA 90503.
J. S. Schoenwald, E. J. Staples, and J. Wise are with Rockwell International Corporation, Thousand Oaks, CA 91360.

## I. Introduction

THE APPLICATION of a surface-acoustic-wave (SAW) oscillator in a commercial Transit satellite marine navigator and the test results will be presented.

The MX1102 marine navigation system receives signals from the Transit satellites [1] in the UHF band at 400 MHz. The Transit satellites circle the earth in 107-min polar orbits at an altitude of 600 nmi. The orbits do not

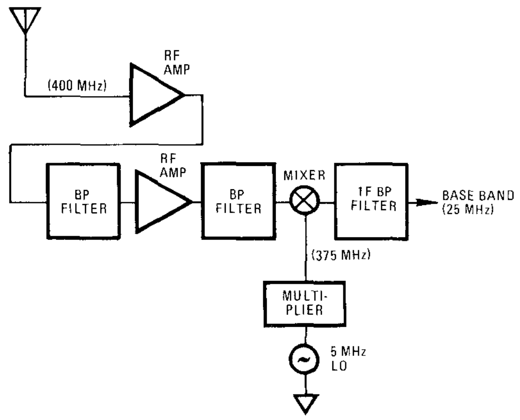



Fig. 1. Block diagram of RF section of navigation receiver.

rotate with the earth so that every point on the earth's surface passes under each of the six orbits approximately twice a day. The signal transmitted by the satellite contains orbital information regarding the location of the satellite and the Greenwich Mean Time. Updating by ground station keeps the information accurate. The navigation receiver detects the signal and obtains the location of the satellite as a function of time. Using this information the receiver calculates its location in a least square solution which best fits the Doppler shifts [2] observed in the satellite signal. In addition to location fixes thus obtained, the navigator also provides dead reckoning between fixes based on inputs of the ship's speed and heading.

In the detection process, the RF signal from the satellite is first down-converted to 25 MHz by the use of a mixer and a local reference signal at 375 MHz. Since the Doppler shift rate is generally small (8 kHz/5 min), the stability of the local oscillator directly determines the accuracy of the system fix accuracy. Therefore, a high stability LO is required. Fig. 1 is a block diagram of the RF section of the navigator receiver. The local oscillator signal is currently generated by multiplying a precision 5-MHz quartz bulk-wave oscillator output up to 375 MHz. This approach suffers from the large volume occupied by the crystal oscillator and the associated multiplying chain and its relatively high cost in addition to the spurs the multiplier generates.

These problems can be solved by replacing the crystal oscillator and the multiplier chain by a more compact SAW oscillator with a fundamental frequency at 375 MHz. This technique leads to potential cost savings due to the ability to batch process SAW resonators. The critical requirements for the local oscillator are stabilities of $1E-10$ for 1 to 100-s averaging time, $7E-10$ for 1000-s averaging time, and an aging rate of $2E-9$ per day (0.73 ppm per year). The oscillator frequency is required to be within 1 ppm of 375 MHz because of the limited passband of IF stages.

## II. Saw Resonator

For this purpose, SAW resonators [3] were fabricated on ST-quartz. The resonance frequency of the resonator follows a quadratic temperature dependence with a second-order coefficient of $-0.03$ ppm/°$C^2$ around the temperature turning point at which $df/dT$ vanishes. The oscillator together with the resonator is ovenized at the turning point for optimal stability. The turning point temperature is determined by the angle of the crystal cut.

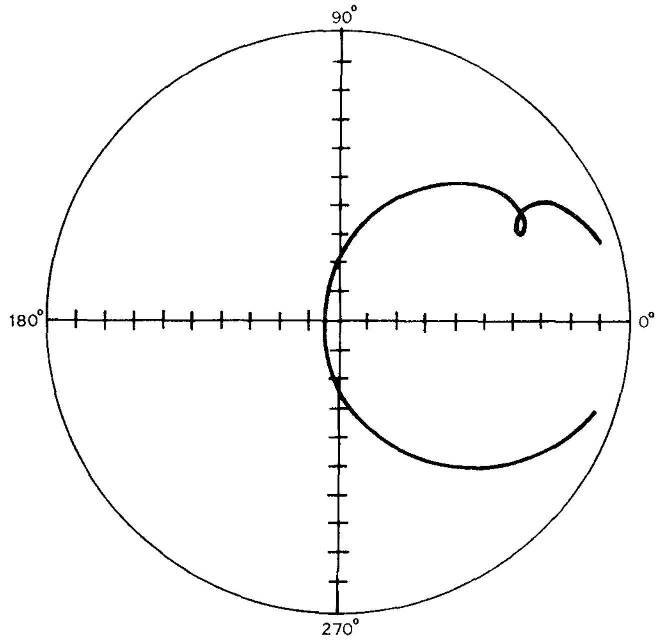



Fig. 2. Smith chart response of a SAW resonator showing 50-Ω impedance at series resonance.

The resonators fabricated are single-port devices using shallow groove reflective gratings. They were cut to provide a 75°C turning point and sealed in evacuated *TO*-5 cans. The single-port resonator [4] was chosen over a two-port delay line because of its higher $Q$ which means higher stability, lower gain requirement, less oscillator components and lower cost. The similarity between the one-port resonator and the bulk-wave crystal also makes it possible to adopt proven crystal oscillator circuits with minimal alterations. The resonator was designed to operate at its series resonance mode with a series impedance of about 50–100 Ω.

During the fabrication process, over 200 transducers consisting of metalized patterns (40 Å of Cr and 1000 Å of Al) are photolithographically formed on a 2×2-in quartz substrate ($x$-propagating, 34° rotated for 75°C turnover). After spot-check probing of random devices, a second masking with photoresist is used to protect the transducers during $CF_4$ plasma etching to form grooves in the reflector portion of the device. Following etching, the resist is removed and the wafer is spot probed again. The wafer is then diced into chips which are mounted on *TO*-5 headers using Abelbond 71-1 high temperature polyimide adhesive which is cured at 325°C. A lower power $CF_4$ plasma etch is used to place the mounted crystal on frequency just prior to sealing. Bakeouts before and after sealing are performed at 125°C for 24 h. Fig. 2 shows the typical polar Smith chart response of the $S_{11}$ scattering parameter of a sealed SAW resonator. The resonance frequency is represented near the origin with slightly less than 50-Ω impedance and a $Q$ about 15 000. The small high frequency side lobe in the form of a loop in the first quadrant does not cause any mode jumping problems because of its much higher series impedance.

## III. Oscillator

Various oscillator circuits were built for the SAW resonator to determine the configuration that would provide the best frequency stability. The common-collector Colpitts oscillator [5] was finally chosen because of its relative simplicity and the ease with which circuit analysis and diagnosis can be performed. This convenience enables one to correct circuits that either do not oscillate, oscillate at spurious modes or off resonance frequency.

In the typical Colpitts circuit one terminal of the resonator is connected to the base of the oscillator transistor. The other terminal is grounded. If the resonator is disconnected from the oscillator circuit, the reflection coefficients of the resonator, $S_{11}(R)$, and the oscillator base, $S_{11}$ (0), can be measured individually. Let $V_i(R)$ and $V_r(R)$ be the incident and reflected voltage waves of the resonator. Similarly $V_i(0)$ and $V_r(0)$ for the oscillator transistor base. The conditions for sustained oscillation are $V_r(R)=V_i(0)$ and $V_i(R)=V_r(0)$. Equivalently, $V_r(R)/V_i(R)=V_i(0)/V_r(0)$ or $S_{11}(R)=1/S_{11}$ (0). This is the condition we will use for our circuit analysis. Normally the magnitude of $S_{11}(0)$ is greater than unity due to negative resistance or gain. Thus $1/S_{11}(0)$, measured at several input levels, is plotted in a polar Smith chart as shown in Fig. 3. The input levels are indicated in units of dBm. The lower gain (larger radius) at a higher input level (e.g., $-10$ dBm) is due to the AGC of the oscillator circuit. Subsequent to plotting $1/S_{11}(0)$, the reflection coefficient of the resonator with its matching network, $S_{11}(R)$ can be measured at various frequencies around the resonance and plotted on the same polar chart. At the point of intersection, the condition $S_{11}(R)=1/S_{11}$ (0) is met and the recombined resonator/oscillator system will oscillate. The point of intersection also defines the oscillator frequency and the power fed into the resonator.

This procedure makes it very simple to design a Colpitts circuit for a given frequency and power level. For circuits that do not oscillate properly, it also serves as a diagnostic tool to identify the problem.

After the SAW oscillator was built, initial attempts to replace the crystal oscillator with a SAW oscillator were hampered by temperature turning point shifts (to be discussed later) and excessive voltage and load dependences. These problems were traced to circuit component variations which are relatively unimportant for crystal oscillators but become significant for SAW oscillators because of the lower $Q$. High resonator drive levels on the order of $-5$ dBm into 50 Ω were also found to degrade the device over extended operation. Metal migration and subsequent crystalite formation are suspected to be the cause of the degradation.

These problems were solved by stabilizing the oscillator with an AGC circuit which limits the power into the SAW

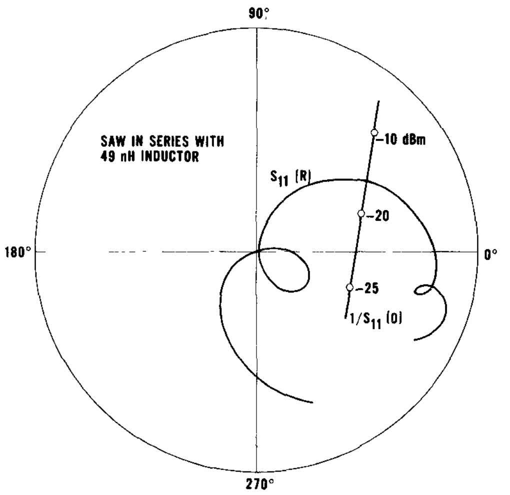



Fig. 3. Reflection coefficients of resonator and oscillator with input level of oscillator amplifier in dbm. The point of intersection defines the conditions at which oscillation takes place.

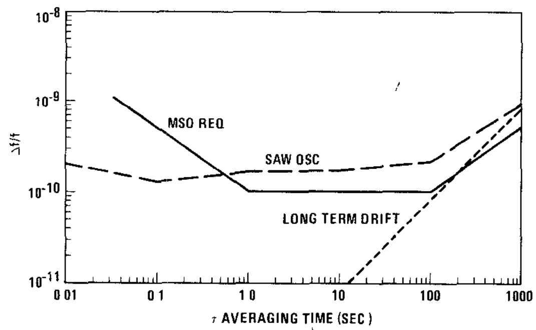



Fig. 4. Typical oscillator stability curve after one-week resonator aging.

resonator to $-15$ dBm. The device degradation is thus eliminated. The AGC circuit is also designed to provide compensation for oscillator frequency shift due to supply voltage change. The compensation scheme makes the phase shift through the oscillator amplifier a quadratic function of the supply voltage with a turnover at the designed voltage. This provision relaxed the voltage regulation requirement from a previous 0.1 mV to 7 mV for a degradation in oscillator stability of less than $1E-10$.

The problem of temperature turning point shift is caused by a linear temperature dependence of the oscillator circuit. This can be seen from the following considerations. If the phase shift provided by the oscillator amplifier is temperature independent, the constant phase shift can normally be cancelled by the use of a passive element to give an overall zero phase in the narrow band of interest. The temperature dependence of the oscillator output frequency $f$ will then follow that of the resonator. Thus

$$f=f_0+a(T-T_0)^2 \tag{1}$$

where $f_0$ is the resonance frequency at turning point $T_0$ and $a$ is the second-order temperature coefficient with a value of $-0.03$ ppm $f_0/°C^2$ for ST-cut quartz. If, however, the amplifier phase shift has a temperature dependence it can generally be approximated by a linear term $b(T-T_0)$. Zero phase requirement around the resonator–amplifier loop implies that

$$\begin{aligned} f &= f_0 + a(T-T_0)^2 - b(T-T_0)\, df/d\phi \\ &= f_0 - a(b/2a)^2 (df/d\phi)^2 \\ &\quad + a(T - T_0 - (b/2a)(df/d\phi))^2. \end{aligned} \tag{2}$$

Here $df/d\phi$ is the inverse of the phase slope of the resonator. The temperature turning point at which $df/dT = 0$ is seen to have shifted from $T_0$ to $T_0 + (b/2a)(df/d\phi)$ due to the temperature dependence of the amplifier phase shift. Qualitatively the new turning point is where the temperature dependence of the oscillator amplifier cancels exactly that of the resonator.

At first glance, one might consider ovenizing the oscillator at the new shifted turning point. However this approach cannot provide the optimal frequency stability because a small fluctuating temperature differential between the amplifier circuit and the resonator can upset the cancellation mentioned above severely and result in poor oscillator stability. For example assume that the amplifier temperature is constant and the resonator temperature fluctuates about the new turning point by $\Delta T = 0.01°C$. In the absence of a turning point shift, the corresponding frequency fluctuation would be $(a\Delta T^2/f)$ by (1) or $3E-12$ which is acceptable. If there is a 1°C turning point shift, the resonator is no longer at its own turning point and the frequency fluctuation would be $(2a \times 1°C \times \Delta T)/f$ or $6E-10$ exceeding the oscillator specification. It was judged that a 0.1°C turning point shift for a frequency fluctuation of $6E-11$ would be acceptable for our applications.

The AGC circuitry provided a constant gain for the oscillator amplifier regardless of temperature. As a result the temperature dependence of the amplifier phase shift, which is just the imaginary part of the same gain function, also decreased. Correspondingly, a reduction of the turning point shift from 10°C to an acceptable 0.1°C was observed.

The problem of frequency shift due to load variation was reduced to $1E-9$ for a 20-percent change in load impedance by the addition of a common base output buffer stage which further decoupled the load from the oscillator stage. Short term stability of 1 to $2E-10$ and aging rates of $3E-8$ per day [6] at 75°C were then achieved routinely.

Fig. 4 shows a typical stability curve after aging one week. The long term drift, which is the limiting factor for the stability at 1000-s sampling time, generally improves by a factor of 4 after aging one month.

## IV. Hybrid Packaging

In order to take the full advantage of the reduction in size that a SAW resonator can offer, hybrid packaging is necessary [7]. A hybrid oscillator package was built that contains the oscillator, buffer amplifiers, the temperature controller, the heater, the voltage regulator, provision for frequency adjustment, and a frequency divider all within a $1.8 \times 1.8 \times 0.65$-in package. A block diagram of the hybrid circuit is shown in Fig. 5. The assembled package is shown

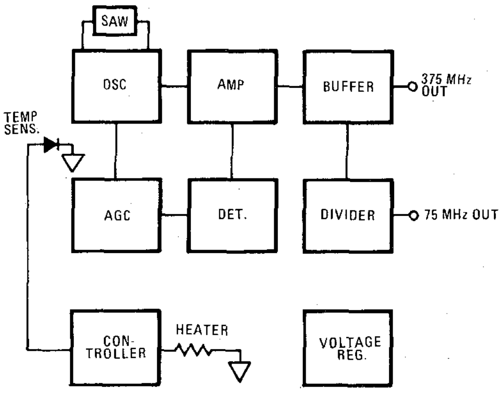



Fig. 5. Block diagram of the hybrid circuit. The 75-MHz output is further divided down to 25 MHz elsewhere for use as an LO signal for the baseband mixing.

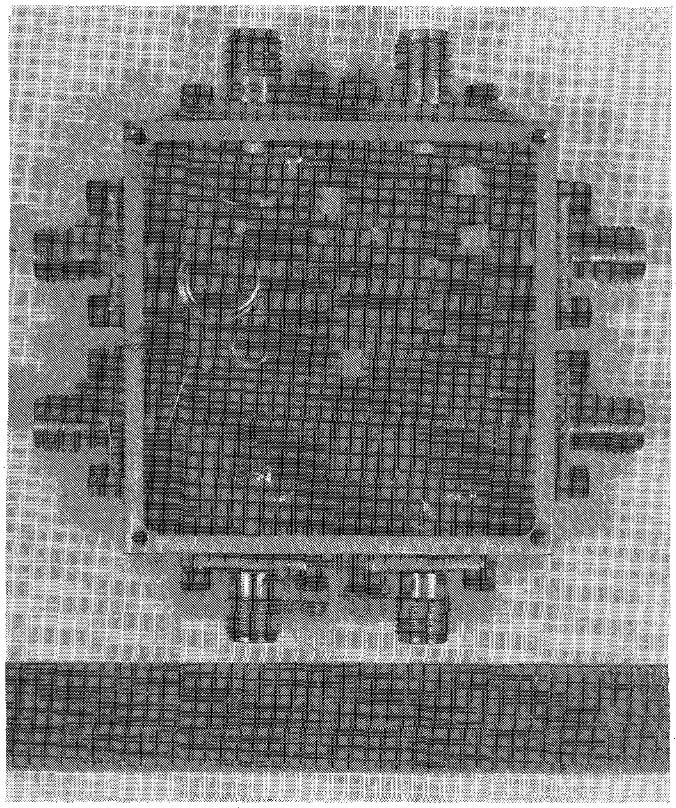


Fig. 6. Photo of assembled SAW hybrid oscillator.

in Fig. 6. Fig. 7 is an exploded view that shows the construction of the hybrid carrier, the oscillator circuit, and the heater board. The design rules for the oscillator board were intentionally conservative with a minimum line width of 0.020 in. Further size reduction is, therefore, possible. Chip resistors and PC boards were used rather than the standard film resistors and ceramic substrates for turnaround time considerations and low heat transfer requirements.

The hybrid construction represents a volume reduction by a factor of twenty over the current production-line crystal oscillator system. This is illustrated in Fig. 8 which shows the crystal oscillator and the RF board. The middle

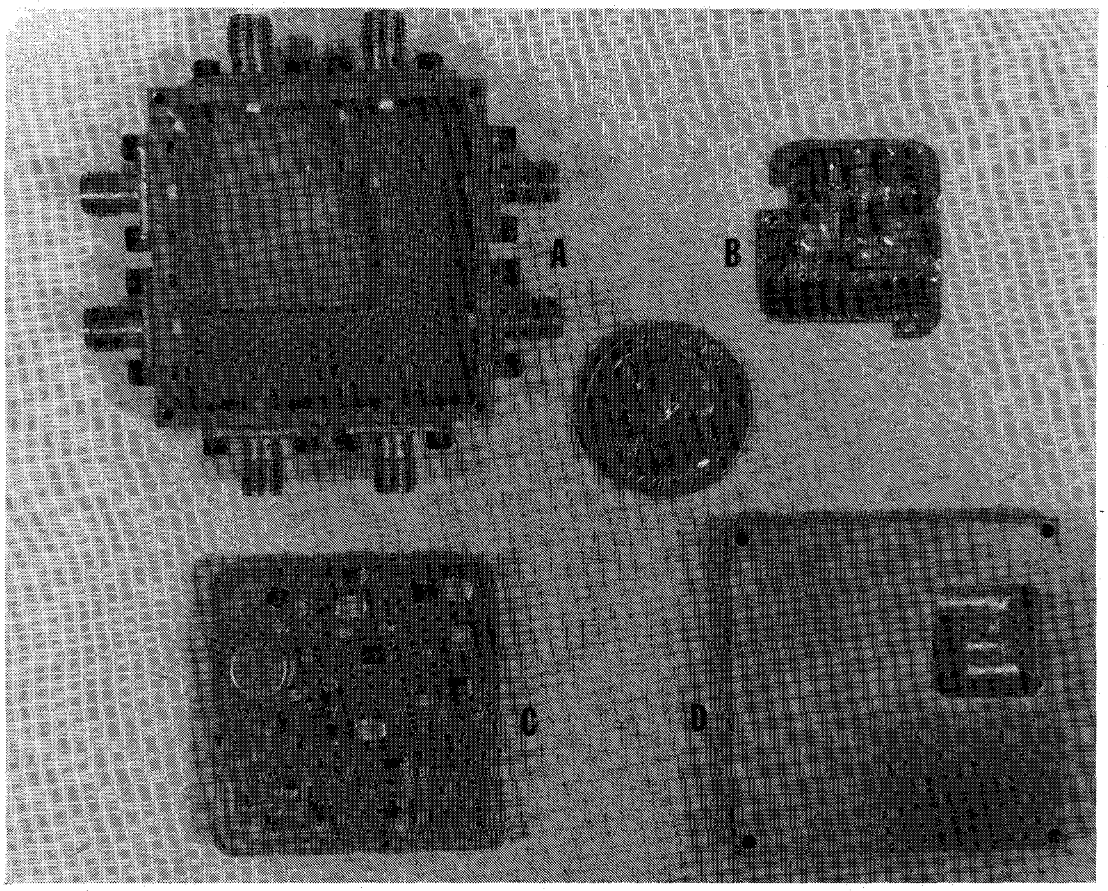



Fig. 7. Photo of SAW hybrid parts. (A) Carrier. (B) Heater. (C) Main board. (D) Carrier cover. The heater fits under the main board in the recess of the carrier.

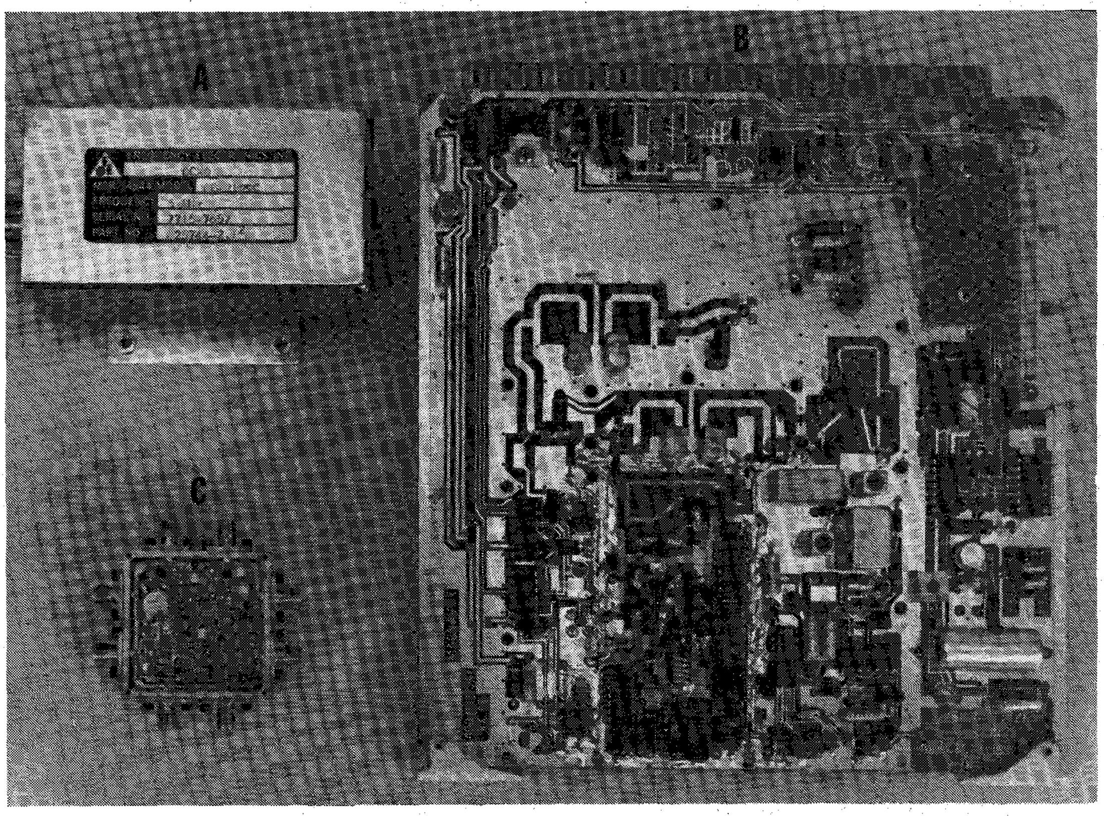



Fig. 8. Size comparison of SAW hybrid oscillator and crystal oscillator with multiplier. (A) Crystal oscillator. (B) RF board with multiplier at the middle-right section. (C) Hybrid SAW oscillator.

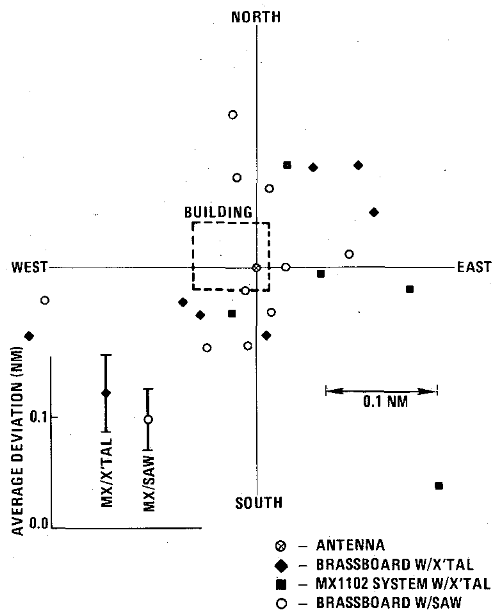



Fig. 9. Comparison of system fixes using SAW and crystal oscillators. Lower left inset shows average deviations of the fixes from the antenna position for both systems.

right portion of the board is the multiplier circuitry. The $g$-sensitivity of the hybrid oscillator was measured through phase noise measurement at 100 Hz. The corresponding fractional frequency change was found to be less than $5E-9/g$ along all three axes of the hybrid package.

The $g$-sensitivity at this level is comparable to AT-cut quartz bulk-wave oscillators. Possible ways to reduce the $g$-sensitivity further will be studied by making the circuit assembly mechanically more rigid.

## V. Comparison Test in System Performance

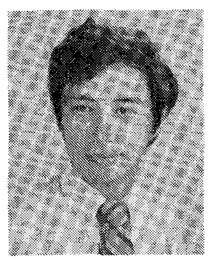
The bulk-wave crystal oscillator and its multiplier chain in the MX1102 navigator were replaced by the SAW oscillator with its simpler divider circuitry. Satellite tracking and fixes were obtained before and after the replacement. The error of the fixes was calculated for both arrangements. The system accuracy for the location fixes with the SAW oscillator was as good as the bulk-wave crystal oscillator. The standard deviation for both arrangements was on the order of 0.1 nmi at night during a period when the sun spot activity was relatively high. Fig. 9 is a plot of the position of the fixes obtained with the crystal oscillator and the SAW oscillator in relation to the receiver antenna location. The average deviation of the fixes for both arrangements is shown in the lower left corner. Within experimental error, the SAW oscillator and the crystal oscillator provide comparable accuracy.

## VI. Conclusion

The use of hybrid SAW oscillators has been demonstrated in marine satellite navigation systems that require precision local oscillators with a short term stability of $1E-10$. In order to lengthen the period between service calibrations, the future work will concentrate on reducing the long term drift rate to $2E-9$ per day at 75°C after 30 days preaging. It is believed that this can be achieved by greater surface cleanliness and better electrode stability.

## References

[1] T. A. Stansell, "The many faces of transit," *Navigation*, vol. 25, p. 1, 1978.
[2] W. H. Guier and G. C. Weiffenbach, "A satellite doppler navigation system," *Proc. IRE*, vol. 48, p. 4, 1960.
[3] W. J. Tanski, "UHF SAW Resonator and applications," in *Proc. 34th Ann. Symp. Freq. Contr.*, p. 80, 1980.
[4] E. J. Staples, "UHF SAW Resonators," in *Proc. 28th Ann. Symp. Freq. Contr.*, p. 280, 1974.
[5] M. E. Frerking, *Crystal Oscillator Design and Temperature Compensation*. New York: Van Nostrand Reinhold, 1978, p. 76.
[6] J. S. Schoenwald, A. B. Harker, W. W. Ho, J. Wise, and E. J. Staples, "Surface Chemistry Related to SAW Aging," in *1980 Ultrasonics Sym. Proc. IEEE* Cat. No. 80CH1602-2, p. 193, 1980.
[7] S. J. Dolochycki, E. J. Staples, J. Wise, J. S. Schoenwald, and T. C. Lim, "Hybrid SAW Oscillator fabrication and packaging," in *Proc. 33 Ann. Symp. Freq. Control*, p. 374, 1979.



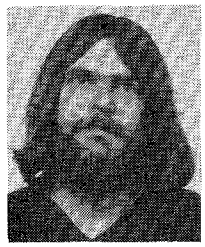
**Binneg Y. Lao** was born in Szechuan, China, in 1945. He received the B.S. degree in physics from the University of California, Los Angeles, in 1967, the M.A. and Ph.D. degrees in physics from Princeton University, Princeton, NJ, in 1969 and 1971, respectively.

Since joining Magnavox in 1980, he has engaged in research programs on SAW oscillators and GaAs IC designs. Prior to joining Magnavox, he was with Bendix Advanced Technology Center and Dow Chemical Eastern Research Center for seven years. During this period, he was involved in the development of SAW devices, NMR and SAW gyros, ion mass-flow and pressure sensors and development of analytical instrumentation involving X-ray fluorescence, IR, ultrasonics and electron beams. He was a Post-Doctoral fellow at the University of Maryland investigating optical properties of alloys and liquid crystals transitions. At Princeton and MIT he worked on exciton effects and far-infrared mixing in semiconductors.

He is a member of American Physical Society and Phi Beta Kappa.

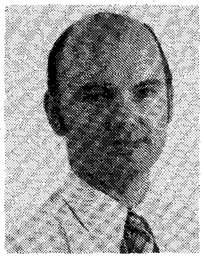
**Neal J. Schneier** graduated from the University of California at Irvine, with a Masters in physics in 1976.

He was engaged in charge coupled device images testing and characterization at Rockwell International, and digital CCD design and testing at TRW. Since working at Magnavox, he has done digital and analog GaAs design and testing, NMOS and CMOS/SOS design, IC computer-aided design system development, and SAW oscillator research.



**David A. Rowe** received the B.S. degree in physics and mathematics from Bowling Green State University, Bowling Green, OH, in 1977. He then went to California Institute of Technology, Pasadena, CA, for graduate study in physics.

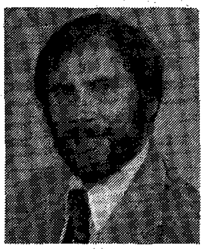
Since joining Magnavox in 1979, he has engaged in research programs on medical ultrasound arrays, surface acoustic wave oscillators, GaAs IC design and device models. He was a computer programmer at Bowling Green and conducted X-ray astronomy research and investigations in energy transfer mechanisms in Seyfert Galaxies at Caltech.



**Robert E. Dietterle** (M'65) received the B.S.E.E. degree from Loyola University, Los Angeles, CA, in 1965.

He joined Magnavox in 1975 and is currently the Manager for the Microelectronics Development Department. He has more than 14 years of experience in the microelectronics area with special emphasis on high frequency hybrid circuit design and fabrication, including thin and thick film processing. While with the Autonetics Division of Rockwell, he had the primary responsibility for the successful solving of many problems encountered in RF hybrid design, interface, and reproducibility areas; and generated the necessary application/design guidelines. He was responsible for the design and development of an all-hybrid UHF Transceiver for military communication systems, a 32-MHz frequency multiplier for the Condon Radar Program, and development of the hybrid design and packaging techniques for the Space Shuttle Power Controllers.

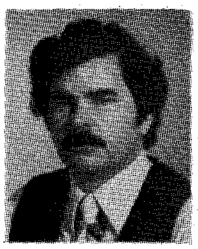
He is a member of ISHM (International Society for Hybrid Microelectronics).



**Jeffrey S. Schoenwald** (M'76) was born in Brooklyn, NY, on March 3, 1947. He received the S.B. degree in physics in 1967 from the Massachusetts Institute of Technology, Cambridge, MA and the M.S. in 1969 and the Ph.D. in 1973, both in physics, from the University of Pennsylvania, Philadelphia, PA.

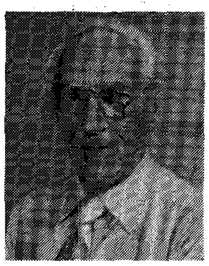
In 1974, he joined the Central Research Laboratory of Texas Instruments, Dallas, TX, where he engaged in surface acoustic wave resonator research. In 1976, he joined Teledyne MEC, Palo Alto, CA, where he conducted research and development of SAW filters, resonators, oscillators and acoustooptic Bragg cell devices. Since 1978 he has been with Rockwell International, Thousand Oaks, CA, and has been engaged in research on SAW resonators, sensors and oscillators, RF magnetron sputtering of thin film piezoelectrics and semiconductors and optical fiber communications devices. He is the author of thirty papers and two patents on aspects of SAW resonator technology.

Dr. Schoenwald is a member of Sigma Xi, the American Physical Society, and the American Vacuum Society.



**Edward J. Staples** (M'70) was born in San Francisco, CA, on June 29, 1943. He received the B.S.E.E. degree from Loyola University in 1966; the M.S.E.E. degree from the University of Arizona, Tucson, in 1968; and Ph.D. degree from Southern Methodist University, Dallas, TX, in 1971.

From 1970 to 1974 he was the Central Research Laboratory of Texas Instruments in Dallas, TX, working on surface wave devices for signal processing. From 1974 to 1976 he was with Piezo Technology, in Orlando, Fl, working on monolithic crystal filters using SAW resonators. Since 1976 he has been with the Rockwell Science Center, in Thousand Oaks, CA, where he has been involved with research and development of SAW resonators and oscillators.



**Jack Wise** (A'79) was born in Newton, NC, on October 25, 1916. He completed a U.S. Government course in electrical engineering in 1941 and was employed immediately by the Naval Research Laboratory, Anacosta Air Base, Washington, DC, as a field engineer. He was self-employed after World War II until 1965 at which time he joined Texas Instruments in Dallas, Texas, as a senior research assistant. From 1974 to 1976 he was with TRW in Redondo Beach, CA, where he was an associate engineer working on SAW devices. Since 1977 he has been with the Rockwell Science Center, Thousand Oaks, CA, as a senior technical specialist working on SAW resonators and oscillators.

# Analysis of Microstrip Circuits Coupled to Dielectric Resonators

RENÉ R. BONETTI AND ALI E. ATIA, SENIOR MEMBER, IEEE

*Abstract*—**A lumped element circuit model is introduced to represent coupling between a cylindrical dielectric resonator and a microstrip line. The external $Q$ of the structure is computed and compared to experimental data obtained with three different resonators.**

Manuscript received April 13, 1981; revised August 6, 1981. This paper is based upon work performed at COMSAT Laboratories under the sponsorship of the International Telecommunications Satellite Organization (INTELSAT).

The authors are with the Communications Satellite Corporation, COMSAT Laboratories, Clarksburg, MD 20734.

## I. Introduction

THE RECENT AVAILABILITY of low-loss, temperature-stable dielectric materials has encouraged the development of several microwave devices employing high dielectric constant resonators. Among the explored applications are temperature-compensated oscillators [1]–[3], low-noise microwave synthesizers [4], and narrow-bandpass filters [5]. These new devices utilize cylindrical dielectric resonators coupled to a transmission line which is generally

0018-9480/81/1200-1333$00.75 ©1981 IEEE