DEVELOPMENT OF AN ATOMIC RUBIDIUM VAPOUR FREQUENCY STANDARD AT NPL OF INDIA USING INDIGENOUS SOURCES

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ABSTRACT

The National Physical Laboratory (NPL) of India is responsible for disseminating, maintaining and developing standards of time and frequency. One of the major activities of the Time and Frequency Section of NPL is the development of atomic standards, presently a rubidium vapour frequency standard (RVFS) using indigenous sources available in the country. The standard mentioned above, will not, of course, be a novel contribution of the field of Time and Frequency Standards, but will be first of its kind of India. In this paper, design, development and fabrication of a rubidium vapour frequency standard is described with necessary modifications and adaptations made in the conventional design. The availability of the indigenously developed atomic standards will prove to be very useful in space, meteorological and other research and development work going on in the country.

This project has been undertaken in collaboration with the Indian Institute of Technology, Kanpur (India).

INTRODUCTION

As the custodian of physical standards in our country, National Physical Laboratory (NPL) of India took up the time and frequency standardization project in 1956 on the recommendation of the Indian National Committee for the International Radio and Scientific Union (URSI). Standard time and frequency signals from this station were first transmitted on February 4, 1959 under the code identification ATA, and since then it has been of continuous service to its users. During this period of seventeen years, ATA transmission has gone through several phases of development, more specially so during the last few years. The large gap in the International Time service between Turino (Italy) in the west, Tokyo (Japan) in the east and Irkutsk (USSR) in the north gives considerable importance to this station.

The NPL has various Time and Frequency activities and an overall view of such activities is mentioned in this paper along with the description of indigenous development of an atomic rubidium vapour frequency standards (RVFS). The work on RVFS is being done in collaboration with Indian Institute of Technology (IIT), Kanpur. The design, development and fabrication of the RVFS and its electronics along with the necessary modifications and adaptations made in the conventional design is discussed. The availability of such indigenous atomic standards will prove to be very useful in space, meteorological and other research and development work going on in the country.

AN OVERALL VIEW OF THE TIME AND FREQUENCY ACTIVITIES AT NPL

Figure 1 describes in a nut-shell the time and frequency set-up at NPL. This set up is in two establishments, one at the main building of NPL at Hillside Road which has generation and monitoring facilities, and the other at ATA, Greater Kailash which has generation and dissemination facilities. The two are at about 13 Kms crowfly distance (1).

Time Comparison:

Regular intercomparisons are made between the generation facilities of NPL and ATA via high frequency (HF) transmissions, portable standard and a direct line. Other techniques of time and frequency comparison like television pulse synchronization method (4); FM link which is being set up in collaboration with the Research Department of All

India Radio; and Microwave link (in collaboration with Microwave Section of NPL) are also being developed between the two stations. Some of these techniques of time synchronization and frequency comparison will later be extended to other user organizations as well.

Broadcasting:

The standard time and frequency broadcast (3) from ATA transmitting station is now at three carrier frequencies 5 MHz, 10 MHz and 15 MHz and the peak envelope power of each transmission is 8 kw. There has been a three fold increase in transmission hours from 4 hours/day to 12 hours/day and these will soon be made round the clock. The carrier frequencies and the electronically generated timing pulses are now directly from the atomic cesium standard and can claim the same order of accuracy. The new, completely electronic, time processor is ready to be installed at ATA (4). The details of ATA transmissions are given in Table 1. These broadcasts are being done in collaboration with Overseas Communications Service of Ministry of Communications, Government of India.

Updating of Electronics:

Another significant change during the last few years which was long due is the switch over at ATA from tube electronics to integrated circuit electronics, thus achieving not only reliability and ease of operation and maintenance, but also eliminating cumbersome 240 volts battery system needed for continuous uninterrupted operation of ATA time units. The ATA time system is now based only on two 12 volt batteries.

Generation:

The generation facilities at NPL main building consist of a variety of crystal oscillators which include Hewlett-Packard quartz frequency standards model 105B and Essen Ring quartz oscillators. The measured aging rates of these standards is found to be better than 1×10^{-10}/day. At present, we are limited by having only one atomic cesium standard which is kept at ATA. An additional atomic cesium standard and a rubidium standard will, however, soon be added to the list of standard time and frequency generating devices at NPL and ATA.

Monitoring:

So far, monitoring at NPL was done only at HF and the stations tracked are, besides ATA itself, JJY (Japan); RKW and RWM (USSR); WWV and WWVH (USA); etc. The reception of WWV and WWVH is not very regular and depends very much on weather conditions. A considerable accuracy has been achieved in the last few years in monitoring these stations and an epoch time to within a millisecond is easily realized. This improvement was possible due to the use of time interval counters and externally triggered dual trace or dual beam oscilloscopes. There is always an effort to track as many standard time and frequency broadcasts as possible and keep a log of all these stations.

Recently, intensive studies have been initiated at NPL on LF/VLF monitoring with the help of a Tracor LF/VLF receiver model 599k. VLF stations tracked so far are GBR (England) and NWC (Australia). The local frequency standards at NPL were calibrated against GBR and NWC and accuracy of better than 1×10^{-9} was achieved. As a typical example, the HP 105B oscillator as received had an accuracy of 5.43×10^{-9} (a drift of 88 μ sec. over an observation period of 4 1/2 hours). After setting against GBR an accuracy of 5.16×10^{-10} (a drift of 13 μ sec. over an observation period of 7 hours) was achieved. Since then, a continuous check is being kept on the calibration of these standards against GBR and NWC. Different antenna designs are being studied and tried for good LF/VLF reception. With a good antenna, it should be possible to track a number of LF/VLF stations around the globe.

Portable Clock:

As a part of time synchronization program, a portable clock is being developed at NPL to calibrate clocks which are far away from NPL and cannot be either physically brought or otherwise linked to NPL for calibration. A HP quartz frequency standard model 105B will be used as the frequency source of the portable clock.

Interface Logic Unit:

A time link between the atomic cesium clock at ATA and the All India Radio (AIR) 'Time-Pips' has already been established and now the 'Sixth-Pips' of AIR time signal is derived from the atomic cesium clock. A correction for the propagation time delay, of course, has to be made to get very precise times (3, 5). This work is only a part of the project on achieving a 'time-Coordination' between different time keeping and time using organizations within the country.

Atomic Clock:

The development of atomic clocks using indigenous sources in India has already been started at NPL of India. The work on an indigenous development of a rubidium vapour frequency standard (in collaboration with IIT, Kanpur) is at quite an advanced stage and a laboratory model of rubidium vapour frequency standard is expected to be ready very soon. The development work is described in the next section.

DEVELOPMENT OF RVFS OPTICAL ASSEMBLY

The development of RVFS optical assembly is discussed in the following.

Figure 2 depicts the assembly of various parts and components of the RVFS optical unit on a test bench. This test bench is used for testing various components: rubidium lamp, absorption cell and photo-detector inside RVFS optical unit. The test-bench uses Zeeman pumping principle where the magnetic field and radio frequency field applied to absorption cell are tuned to the proper resonance line.

Detailed discussion of the fabrication of the system is for the hyperfine optical pumping microwave RVFS system.

Principle:

Operation of the rubidium standard is based on a hyperfine transition in rubidium 87 (Rb^{87}) gas. The rubidium vapour and an inert buffer gas (to reduce doppler broadening among other purposes) are contained in a cell illuminated by a beam of filtered light (Figure 2). A photodetector monitors changes, near resonance, in the amount of light absorbed as a function of applied microwave frequencies. The microwave signal is derived by multiplication of the quartz oscillator frequency. A servo-loop is used to connect the detector output and oscillator so that the oscillator is locked to the center of the resonance line.

By an optical pumping technique (15-19), an excess population is built up in one of the Rb^{87} ground-state hyperfine levels within the resonance cell. Population of the F = 2 level is increased at the expense of the F = 1 level. Rb^{87} atoms are optically excited into upper energy states from which they decay quickly into both the F = 2 and the F = 1 levels. Components linking the F = 2 level to the upper energy states are removed by filtering the excitation light. Since the light excites atoms out of the F = 1 level only, while they decay into both, an excess population builds up on the F = 2 level. Because fewer atoms are in the state where they can absorb the light, the optical absorption coefficient is reduced.

Application of microwave energy, corresponding to that which separates the two ground state hyperfine levels F = 2 and F = 1, induces transitions from the F = 2 to F = 1, level so that more light is absorbed. In a typical system arrangement, photodetector output reaches a minimum when the microwave frequency corresponds to the Rb^{87} hyperfine transition frequency of 6.834 GHz.

Resonance frequency is influenced by the buffer gas pressure and to a lesser degree by other effects. For this reason, a RVFS standard must be calibrated against a reference standard, e.g. cesium standard. Once the cell is adjusted sealed, the frequency remains highly stable.

RVFS OPTICAL ASSEMBLY

Optical Unit:

The RB-frequency standard optical unit consists of magnetically shielded region with a Rb^{87} lamp with oscillator, Rb^{85} vapour filter cell and a microwave cavity with Rb^{87} vapour absorption cell placed inside it (Figure 3).

The magnetic shield consists of one outer netic and three inner co-netic cylinders. The co-netic cylinders are used as inner shield because of its high attenuation characteristics. Outer netic cylinder has only medium attenuation, but does not saturate as easily as co-netic. Listing from the inner cylinder to the outer, the diameters are 12, 15, 17 and 20 cms respectively and their respective lengths are 33, 35, 37 and 42 cms. The space between the shielding cylinders is filled with the glass wool. This measure avoids conductive cooling and vibration. The ends of the shielding cylinders are covered with caps of the same shielding material. The only openings in the outer magnetic shield are those for the wires of the necessary supply and control voltages and a small hole to provide access to the tuning shaft of the microwave cavity.

Rb^{87} Lamp:

This lamp consists of bulb blown from a Pyrex tubing to a diameter of 1 cm with the wall thickness of 0.1 mm (Figure 4). The bulb is filled with Rb metal and noble gas at 5 torr. The use of the noble gas lowers the striking potential for the lamp. The lamp is excited by a 100 MHz oscillator. The circuit is very simple and stable.

Filter Cell:

Filter cell is a cylinderical bulb filled with Rb^{85} and argon buffer gas at 50 torr. Addition of the buffer gas to the filter cell broadens and shifts the Rb^{85} absorption lines resulting in an improved filtering effect (Figure 5). When Rb^{87} resonance radiation is passed through the Rb^{85} filter cell, the undesired light component 'a' is absorbed by the component A in the filter cell while the component 'b' which is the desired pumping light is transmitted by the filter cell unobstructed and this pumps atoms mostly out of the F = 1 state of RB^{87} (Figure 6).

Microwave Cavity:

This is a brass cylinder with the outer diameter of 6.5 cm and a total tunable length 9.5 cm. The inside walls of the cavity are highly silver coated. On one side of the cavity there is a perforated tuning plunger which could be operated manually with the help of a shaft for tuning the cavity. The cavity is operated in TE 011 mode (Figure 7). The end plate on the other side has two holes. Through the central hole, light from the Rb^{87} absorption cell falls on the silicon photodiode which monitors the light intensity. The output of the silicon photodiode contains the required frequency correction in terms of the phase and the amplitude of 137 Hz modulation and is one input to the amplifier assembly of the electronic circuitry. The other hole in the end plate is used for providing the microwave input at the frequency 6.834 GHz through an Iris or a loop. Inside the cavity rests a RB^{87} absorption cell containing Rb metal with nitrogen buffer gas at 10 torr. The heater winding on the outer walls of the cavity maintains Rb^{87} vapour absorption cell at the desired temperature. The cavity along with the Rb^{87} absorption cell is placed inside a solenoid which provides the statis magnetic field along the cavity axis. The Q of the cavity has been measured and found to be above 15,000.

Power Supplies:

To run the lamp oscillator, a stabilized regulated power supply is provided. The lamp is run at 200 volts and 40 mA. The temperature of the Rb^{87} vapour absorption cell and Rb^{85} vapour filter cell is maintained through the heaters, powered by stabilized 12 volt, 4 amp. batteries. The temperature is stabilized with the help of a temperature sensor.

RB-lamp, Filtercell and Microwave cavity have been joined together in an orderly form with the help of fiber rings and two brass rods passing through these rings (Figure 8). These rings are tightly fixed inside a solenoid which is covered by magnetic shielding cylinders. The outermost layer of the shield and the panel and semicircular strips on which the unit rests, are of aluminium. The panel is provided with the binding posts for the various connections and wiring. This measure safeguards the unit against acceleration and vibration.

DEVELOPMENT OF ELECTRONICS FOR RVFS

Design and fabrication of electronics for RVFS was carried out as said above at the Advanced Center for Electronics System of the Indian Institute of Technology, Kanpur (7-9). The functional block diagram of the RVFS, as discussed above, is given in Figure 9. RVFS electronics can be functionally discussed into the following separate subheadings.

Voltage Controlled Crystal Oscillator (VCXO):

The short-term stability specification for RVFS is the same as the short-term stability required of the VCXO. The HP-105A, 5 MHz quartz oscillator selected to function as VCXO in the RVFS has a stability of 1×10^{-11} over one-second averaging period and hence meets the RVFS short-term stability specification. The electronic frequency tuning range of this model is 4×10^{-8} for an input control voltage of -5 to +5 V. Coarse screw driver adjustment up to a range of 1×10^{-6} is provided on the front panel. The harmonic distortion and the non-harmonic content are quite low. The unit is temperature controlled and features an aging rate better than 5 X 10^{-10} over 24 hours. It can give 1 V r.m.s. into 50 ohms at 5 MHz.

Temperature and Magnetic Field Control:

The RVFS is required to have a very effective magnetic and electrostatic shielding for the absorption cell to be kept in a high Q microwave cavity. The ultimate long-term and short-term stabilities of the RVFS are dependent upon the good optical assembly.

Frequency Multiplication and Synthesis:

The frequency multiplication and synthesis scheme is shown in Figure 10, which is used to generate the microwave frequency to match the Rb^{87} resonance frequency around 6.83468 . . . . GHz. The 1368 harmonic of the 5 MHz VCXO output is mixed with the output of the 5.314 . . . . MHz programmable frequency synthesizer in a harmonic generator-cum-mixer and the resulting side band viz 6834.68 . . . . MHz is selected by having the microwave cavity in the optical unit resonating at this frequency.

The tuning range and discrete step resolution specification for RVFS dictates the resolution and range to be realized from the programmable frequency synthesizer. A tuning range of 5000 X 10^{-10} and a resolution of 3 X 10^{-10} correspond to around 4 KHz and 2 Hz change respectively, at 6.83468 . . . . GHz. This is achieved (8) by designing the programmable frequency synthesizer tunable over 4 KHz is approximately 2 Hz discrete steps around 5.316 . . . . MHz (See Figure 11).

The Rb^{87} resonance line used as the frequency reference is extremely sharp and has a 3 dB bandwidth of about 25 Hz with the peak around 6.83468 . . . . GHz. The 137 Hz phase modulation of the exciting microwave signal around 6.834 . . . . GHz used to scan the peak of the atomic resonance is designed to have an extremely small modulation index resulting in a peak deviation of about 100 Hz at the excitation frequency. The phase modulated multiplier chain (9) for RVFS is given in Figure 12.

The HP VCXO used has an electronic tuning range of 4 X 10^{-8} for an input voltage range of -5V to +5V. This corresponds to 0.2 Hz in 5 MHz and when multiplied to the Rb^{87} response region results in 274 Hz. The feature of sensing the approach of this electronic tuning limit of the VCXO is provided in the Logic section of the RVFS system monitoring circuitry to be described in a later section. When the cumulative VCXO drift approaches this limit in the RVFS system operation, manual screw driver adjustment of the VCXO frequency is to be made until the error voltage delivered to VCXO is close to zero volt.

The 5 MHz tuned buffer amplifiers in Figure 10, act as distribution amplifiers distributing the VCXO output to the various RVFS subsystems. The 5 MHz output serving as the RVFS output is rectified and given to a panel meter to enable checking the RVFS output amplitude.

Synchronous Error Detection and Control:

Figure 13 shows the synchronous error detection and control scheme. The 137 Hz, harmonics and the noise appearing at the output of the photodiode in the optical assembly is amplified by a low noise A.C. preamplifier, passed through 274 Hz notch filter and a 137 Hz tuned amplifier and then given to the four quadrant analog multiplier used as a phase detector for synchronous phase detector for synchronous phase detection. The 137 Hz phase modulating signal is the reference for this phase detector. The 137 Hz is generated from a stable 274 Hz RC square wave oscillator by dividing it by 2 using a flip-flop and then filtering out the harmonic from the resulting 137 Hz fundamental thereby insuring that the 137 Hz second harmonic is about 70 dB down the fundamental. The filtered 137 Hz is sent to the 137 Hz phase modulator in the 5 MHz frequency multiplier chain through a continuous phase shifter to enable phase adjustments of the 137 Hz phase modulating signal. The phase shifter is capable of providing -180° to $+180^{\circ}$ phase shift. The phase detector output is amplified, passed through a precision loop error integrator and then delivered to the VCXO frequency control input for frequency adjustment consistent with the 137 Hz error signal amplitude and phase.

The preamplifier gain is continuously variable from 20 to 5000 in two steps. The overall gain of the 137 Hz error signal channel until it is fed to the phase detector is variable from around 10^2 to about 750 X 10^3 in two steps. The bandwidth of the 137 Hz tuned amplifier is about 6 Hz. The analog multiplier, the following amplifier and the 274 Hz square wave oscillator functions are derived from a single linear MSI chip. The analog multiplier has a variable gain and output zero adjust feature and the unit has excellent immunity against temperature variations. The loop error integrator employes an IC with excellent drift characteristics. A D.C. drift of about 10 mV at the output of the loop integrator results in a VCXO frequency drift of about 4 X 10^{-11}. The loop integrator time constant is normally one minute but provision is made to change it to one second. When the integrator is set to 1 minute time constant, the output should not drift more than 10 mV when the feedback path is initially shorted and the output voltage adjusted to zero, the short removed, and the output voltage is observed after a minute. The integrator designed and built meets this specification. The outputs of the D.C. preamplifier, 137 Hz tuned amplifier and the filtered 137 Hz reference frequency are sent to the RVFS Logic subsystem.

RVFS System Operation Monitor:

The RVFS system operation monitors the signal levels of importance at various stages in the standard and operates two front panel lights which indicate the status of the system (see Figure 13).

The monitor essentially consists of two logic gates, controlling the status of two lights on the front panel, whose output states are determined by the detected 274 Hz signal level from the optical assembly, the synchronously detected 137 Hz error signal level, the VCXO control voltage level and the 4.816 . . . . MHz frequency synthesizer lock indicating signal level. The voltage comparators, before the logic gates inputs, trip when the above signals exceed the preset levels at the comparators inputs. The preset levels correspond to those levels appearing at the normal operation of the system. The comparators have a small hysteresis. the VCXO input is monitored to provide indication on the panel if the VCXO electronic tuning limit is approached.

From the scheme, it is seen that the combined status of the two front panel lights provides indication of the proper functioning of the system and subsystem operation. When the standard is functioning normally, only the light indicating correct operation of the RVFS is 'ON'. To bring the malfunctioning of the standard even for a very small time to the notice of the operator of the standard, this correct operation indication light remains 'OFF' until it is manually reset when once put 'OFF' as a result of a small interruption on its continuous operation.

Regulated DC Power Supplies:

The RVFS derives its power from five well regulated DC power supplies operating on 230 V, 50 Hz mains. These DC power supplies deliver +28V, +15V, -15V, +5V and -5V and have sufficient output current ratings with adjustable current limit feature.

CONCLUSION

An overall view of Time and Frequency activities at NPL of India is given in a nutshell. The design, development and fabrication of rubidium vapour frequency standard along with its electronics, is described using indigenous sources in India. The development work of RVFS is quite at an advanced stage and the model will be ready soon. The skill and experience gained through the development work of RVFS will help taking up of making better frequency standards like cesium, hydrogen, etc.

The availability of the indigenous atomic standards will save a lot of foreign exchange and will help the ongoing research projects in the country and also in taking up new projects depending upon such available facilities.

ACKNOWLEDGEMENTS:

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Mr. Hukam Singh is thanked for his patient typing.

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TABLE 1

TIME & FREQUENCY SIGNAL DATA OF ATA

Call Sign	:	ATA
Location of the Station	:	Greater Mailash, Delhi N 28° 33' 36" E 77° 18' 48"
Type of Service	:	Experimental
Primary Standard	:	Commercial Atomic Cesium Standard. (HP Model 5061A with option 004)
Other Standards	:	"Essen Ring" type quartz crystals, Commercial quartz standards. (HP Model 105B).
Antenna	:	Horizontal Folded Dipole.
Carrier Power	:	8 KW (Peak Envelope Power).
Carrier Frequency	:	5 MHz, 10 MHz and 15 MHz.
Modulation Frequency	:	1 pps and 1000 Hz.
Time Broadcast	:	11 Hours Per Day on Monday to Saturday. (9:00 - 20:00 IST or: 3:30 - 14:30 GMT). 4 Hours Per Day on Second Saturday of the Month and Sundays. (10:00 - 14:00 IST or 4:30 - 8:30 GMT).
Time Scale Adopted	:	UTC
Accuracy of Time Interval	:	$\pm 1 \times 10^{-10}$
Accuracy of Frequency	:	$\pm 1 \times 10^{-10}$

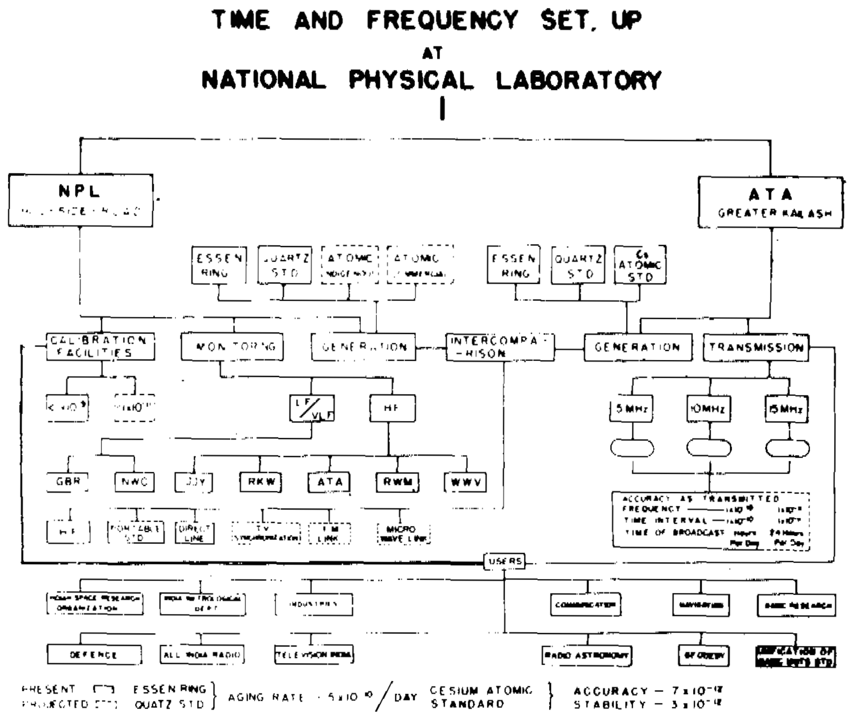

FIGURE 1: Time and Frequency Set Up at NPL of India

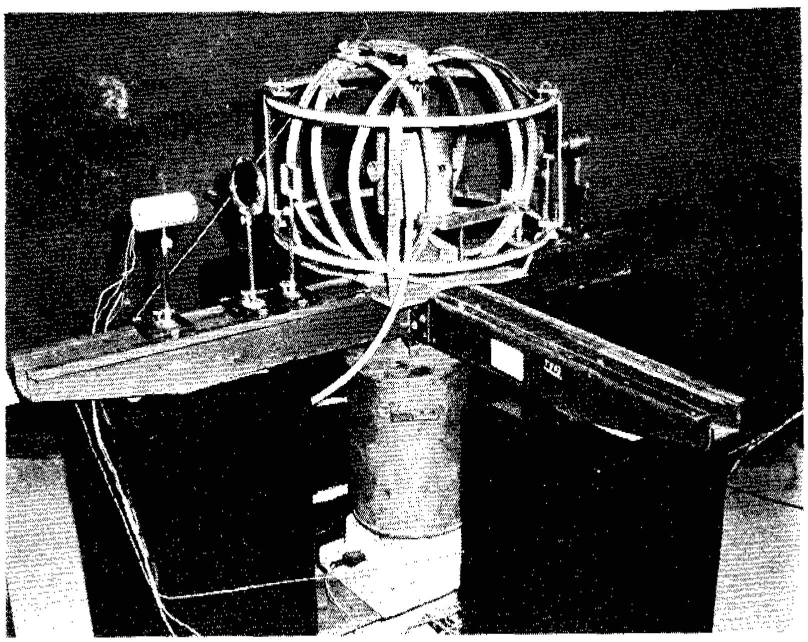

FIGURE 2: Photograph of RVFS Optical Pumping Experimental Set Up

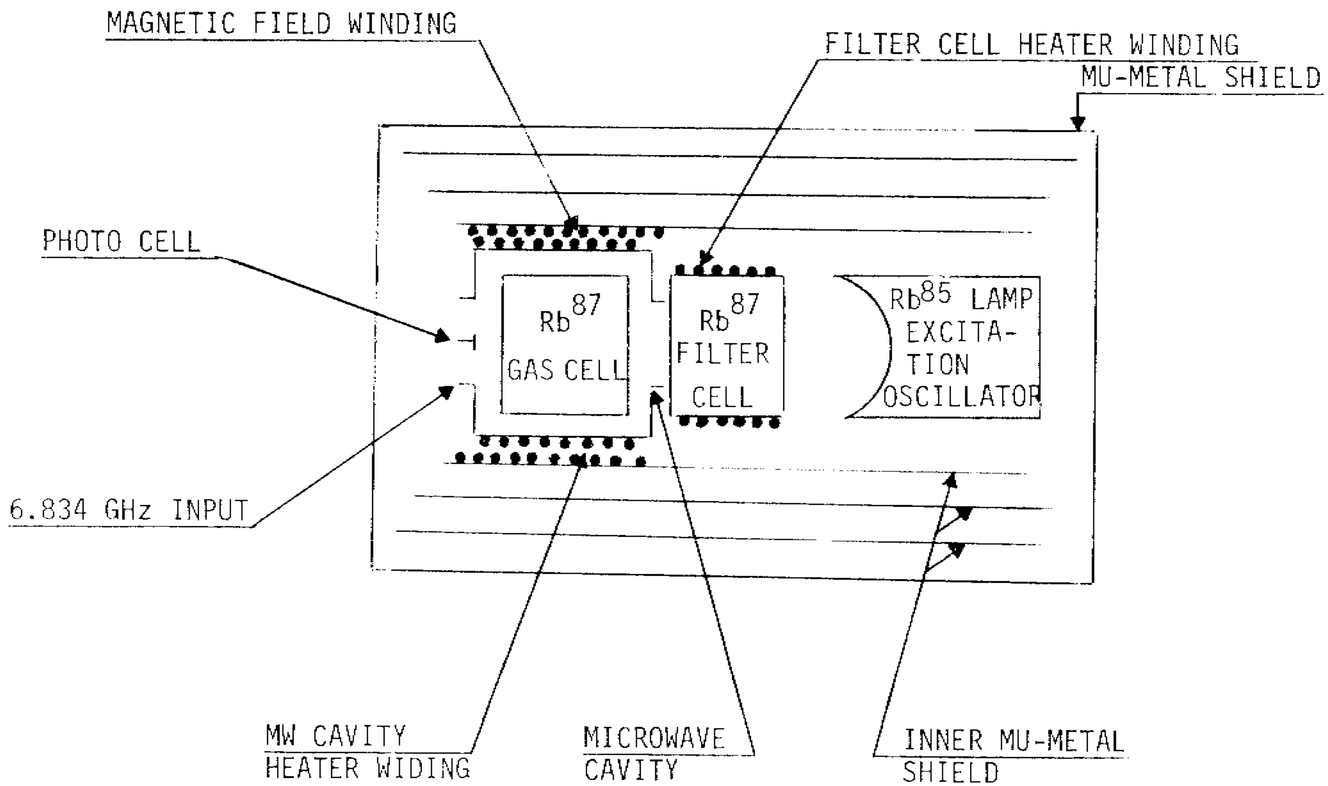

FIGURE 3: Block Diagram of the RVFS Optical Unit

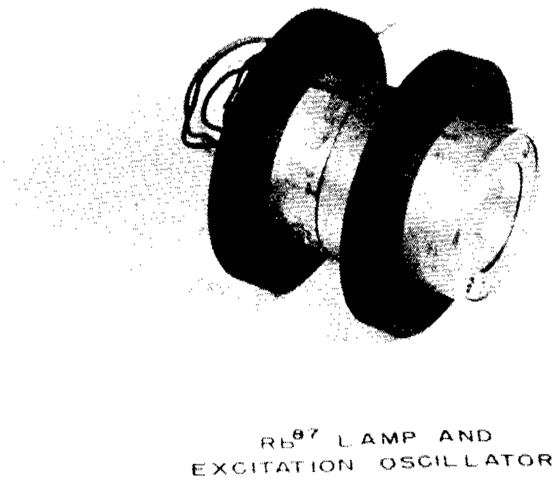

FIGURE 4: Rb^{87} Lamp With Excitation Oscillator

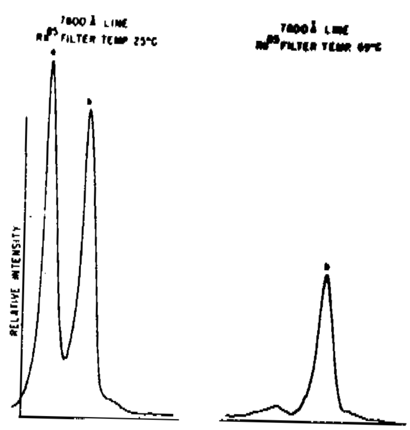

FIGURE 5: Spectra of Rb^{87} Spectral Lamp at Two Rb^{85} Filter Cell Temperatures

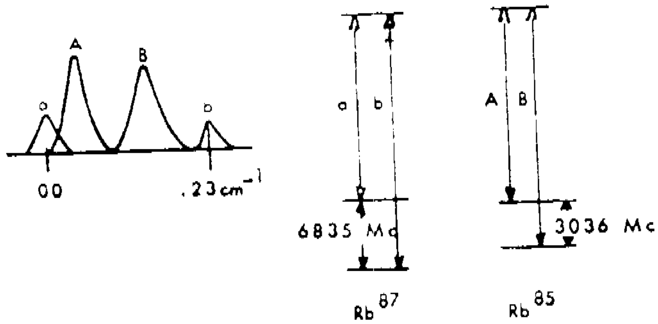

FIGURE 6: Simplified Energy Level Diagram for Rb^{87} and Rb^{85}

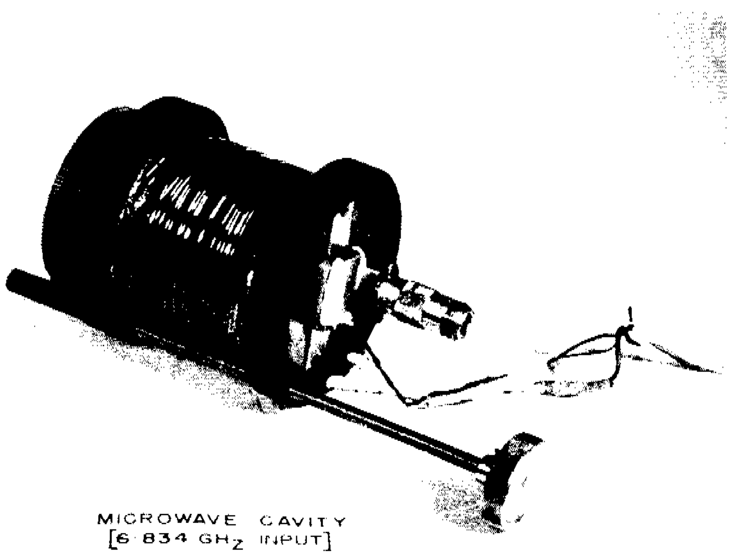

FIGURE 7: Microwave Cavity

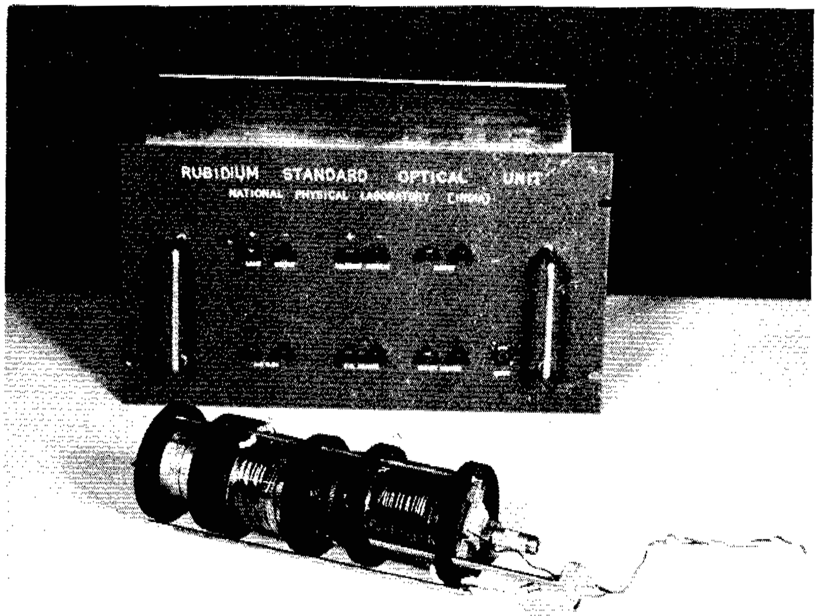

FIGURE 8: Photograph of the RVFS Optical Unit

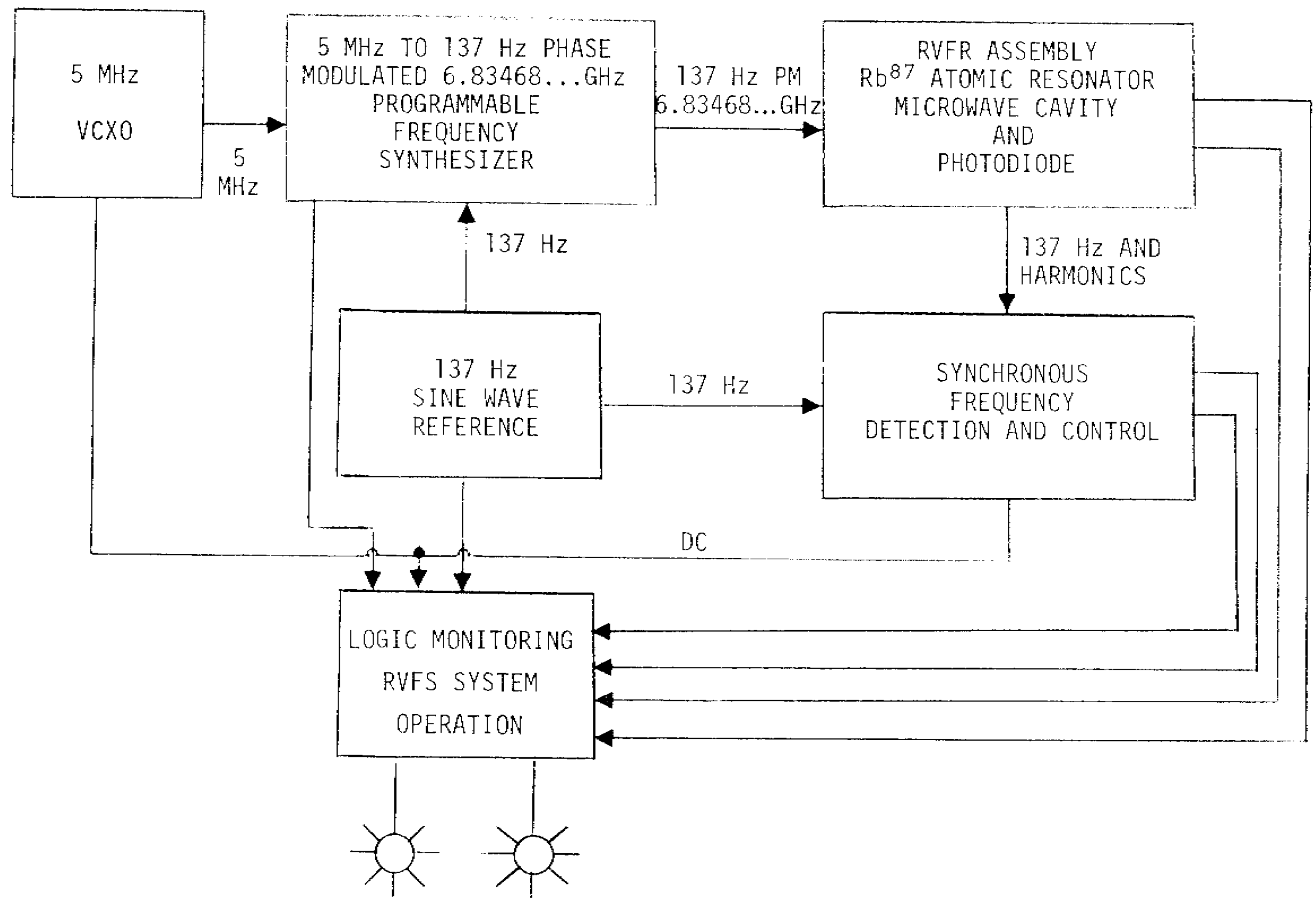

FIGURE 9: RVFS Functional Block Schematic Diagram

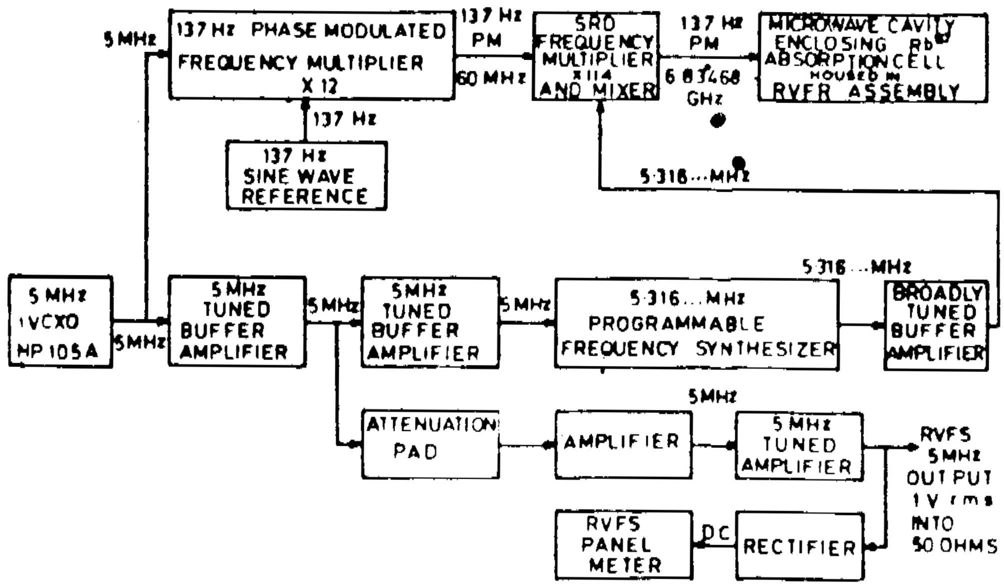

FIGURE 10: Phase Modulation, Frequency Multiplication and Synthesis Scheme for Generating the Excitation Microwave Frequency Around 6.83468 . . . GHz Matching the Rb^{87} Resonance

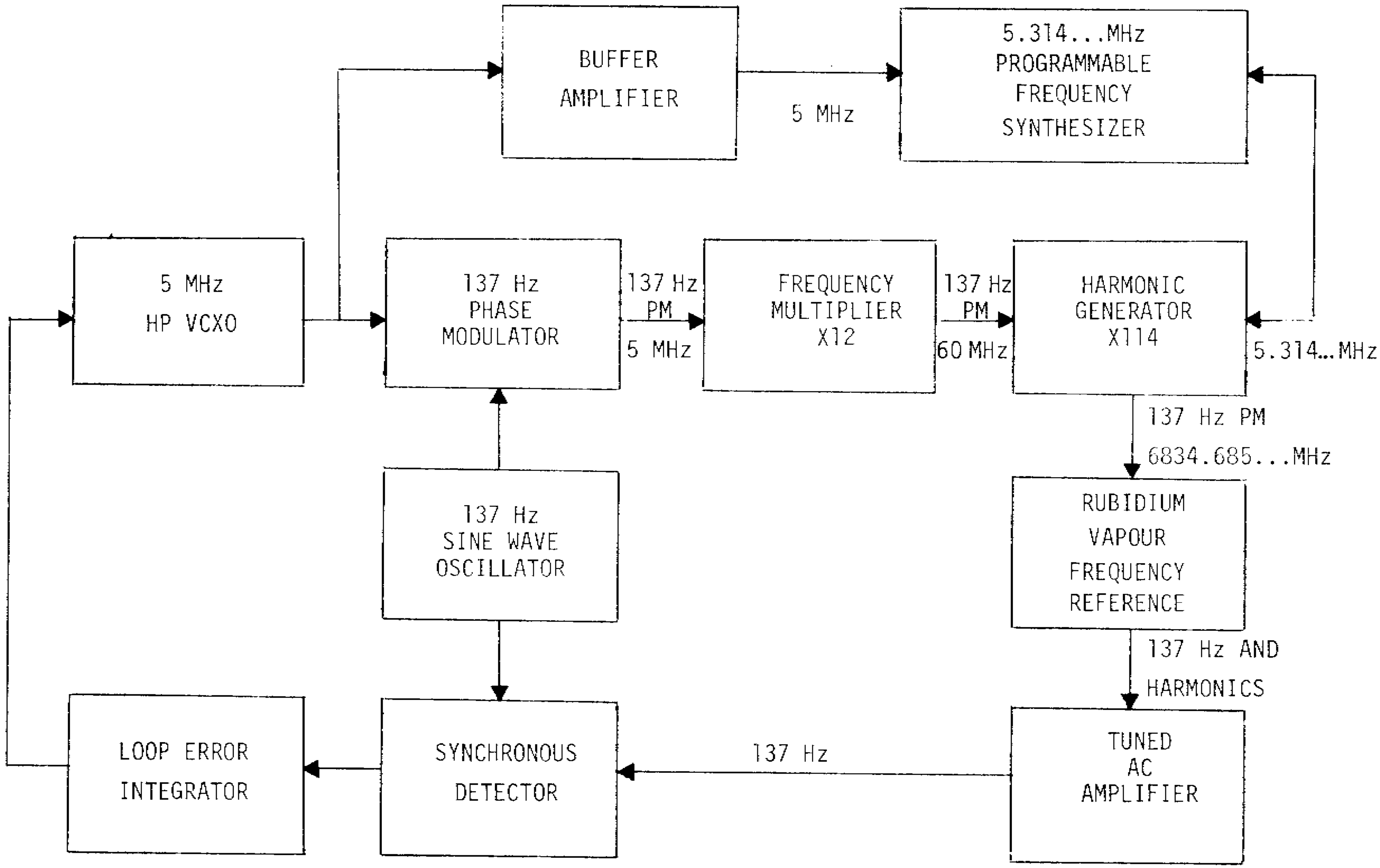

FIGURE 11: Block Schematic of the RVFS With the 5.314 . . . MHz Programmable Frequency Synthesizer

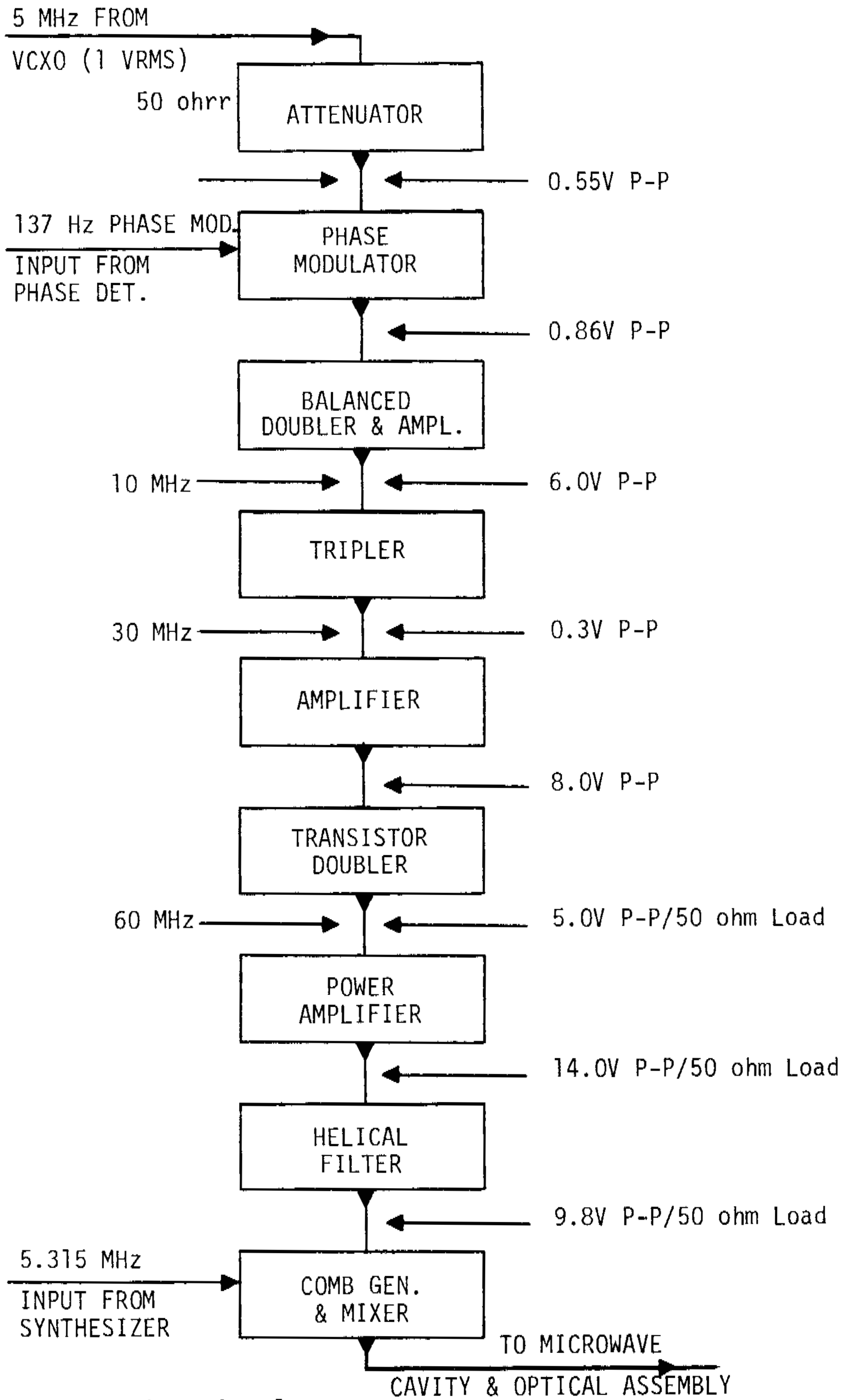

FIGURE 12: Block Schematic of the Phase Modulated Multiplier Chain

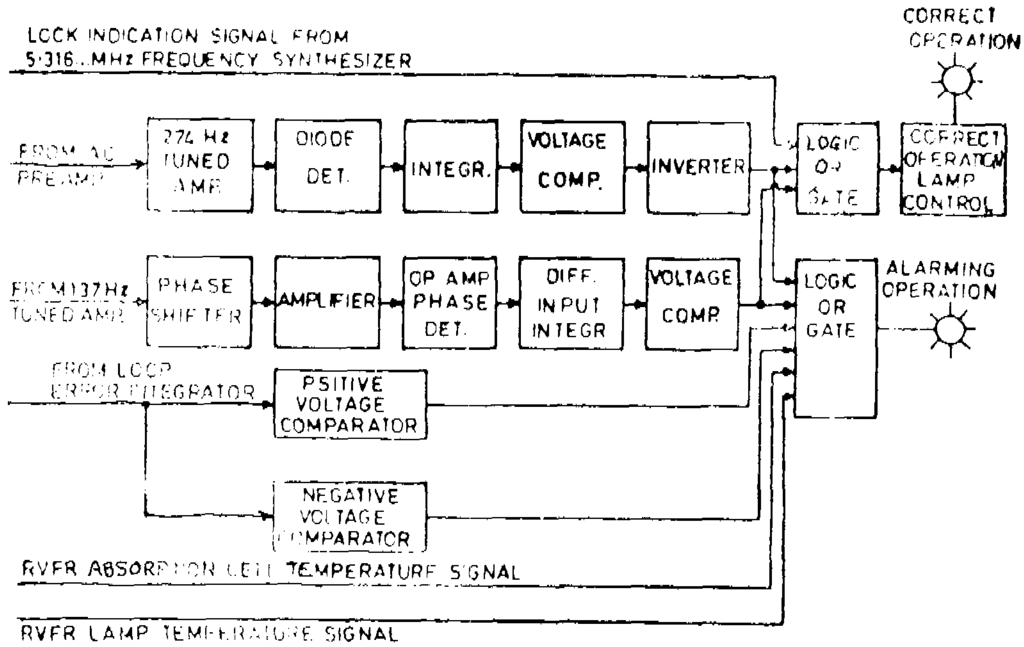

FIGURE 13: RVFS System Operation Monitor