DEMONSTRATION OF THE FREQUENCY OFFSET ERRORS INTRODUCED BY AN INCORRECT SETTING OF THE ZEEMAN/ MAGNETIC FIELD ADJUSTMENT ON THE CESIUM BEAM FREQUENCY STANDARD

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ABSTRACT

The fine frequency setting of a cesium beam frequency standard is accomplished by adjusting the C field control with the appropriate Zeeman frequency applied to the harmonic generator.

A novice operator in the field, even when using the correct Zeeman frequency input, may mistakenly set the C field to any one of seven major Beam I peaks (fingers) represented by the Ramsey curve. This can result in frequency offset errors of as much as 2.5 parts in ten to the tenth.

The effects of misadjustment will be demonstrated and suggestions discussed on how to avoid the subtle traps associated with C field adjustments.

INTRODUCTION

The Hewlett Packard Model 5061A Cesium Beam Frequency Standard is a self calibrating device requiring no other reference frequency to insure its frequency accuracy to within 1×10^{-11} of all other Cesium Beam Frequency Standards. Although this statement is literally correct, it is critically dependent on the magnetic C Field setting. The magnetic C Field is adjusted to the correct central Beam I peak (within one of seven families of Ramsey Curves) with the appropriate Zeeman Frequency applied to the harmonic generator. However, the initial turn on procedure covering this adjustment is inadequately covered in the technical literature. It is further complicated by the fact that selection of undesired cesium atom energy level transitions can result in beam current (Beam I) outputs from the cesium tube of slightly greater than or near equal to the Beam I developed during the desired transition. The incorrect setting of the magnetic C Field can result in frequency error offsets of as little as one part in ten to the eleventh when the incorrect sub-central peak is selected or as much as two and one half parts in ten to the tenth when the incorrect

central peak is chosen. The new Hewlett Packard Cesium Standards (1974 on) with the higher resolution C Field Control will allow an offset which is limited to the adjacent sub-central peak of the desired transition. It should be noted that in every case of erroneously setting the C Field, the Cesium Standard indicates normal operation; continuous operation lamp on, alarm lamp off, and all front panel meter readings of the operating parameters within the normal range.

The purpose of this paper is to describe the means of demonstrating this effect and suggesting the means for avoiding the pitfalls associated with setting of the magnetic C Field. However, before discussing the demonstration it is desirable to review the theory of operation of the standard on a block diagram level, the cesium beam tube details, the hyperfine energy level diagrams of Cs atom 133, and the initial turn on procedure.

OPERATION OF THE CESIUM BEAM FREQUENCY STANDARD

Figure 1 is a simplified block diagram of the HP 5061A Cesium Beam Frequency Standard. The voltage controlled Quartz Oscillator (A10 provides a 5 MHz sinewave to a X 18 multiplier (A3). The multiplier outputs a phase modulated 90 MHz signal to the Harmonic Generator (A4). The 5 MHz from the Quartz Oscillator is inputted to the Synthesizer via a buffer in the Multiplier and both Multiplier and Synthesizer outputs are applied to the Harmonic Generator. Here the phase ($\emptyset$) modulated 90 MHz is multiplied by 102 times and added to the Synthesizer output resulting in a $\emptyset$ modulated 9192.63----MHz being applied to the microwave cavity surrounding the Cesium Beam Tube (A12) interaction region. The Beam Tube acting as a high Q bandpass filter provides discriminator action and outputs the fundamental (137 Hz) and its 2nd harmonic (274 Hz). When the frequency of the injected signal is in agreement with the hyperfine energy level transition of the Cesium Atom the beam tube output is primarily 274 Hz. The 137 hertz output is an error signal proportional in amplitude and direction to the difference in frequency between the injected signal and the Cs atom transition frequency. Both the fundamental and the 2nd harmonic frequencies are amplified in the AC Amplifier (A7). The fundamental is then fed to a synchronous Phase Detector (A8), the output of which is applied to an operational amplifier (A9) where the $\emptyset$ error signal is converted to a DC voltage used to control the Quartz Oscillator (A10) thru VCO action. Thus the frequency stability and accuracy of cesium atom 133 hyperfine energy level transition is transferred to the Quartz Oscillator via the $\emptyset$ locked loop and outputted to the users in the signal format of 5 MHz, 1 MHz, and 100 KHz.

In addition to the phase locked loop, there are four other circuits. Buffer Amplifier (A13) outputs the 5 MHz 1 volt RMS sinewave. The Frequency Divider (A6) takes the 5 MHz input and divides down to 1 MHz and 100 KHz and provides these signals via buffers at 1 volt RMS. Cesium Oven Controller (A11) provides the heat source for cesium atom effusion within the Beam Tube. Finally, the Logic Module (A14) detects fundamental, 2nd harmonic, error signal limits and synthesizer failures.
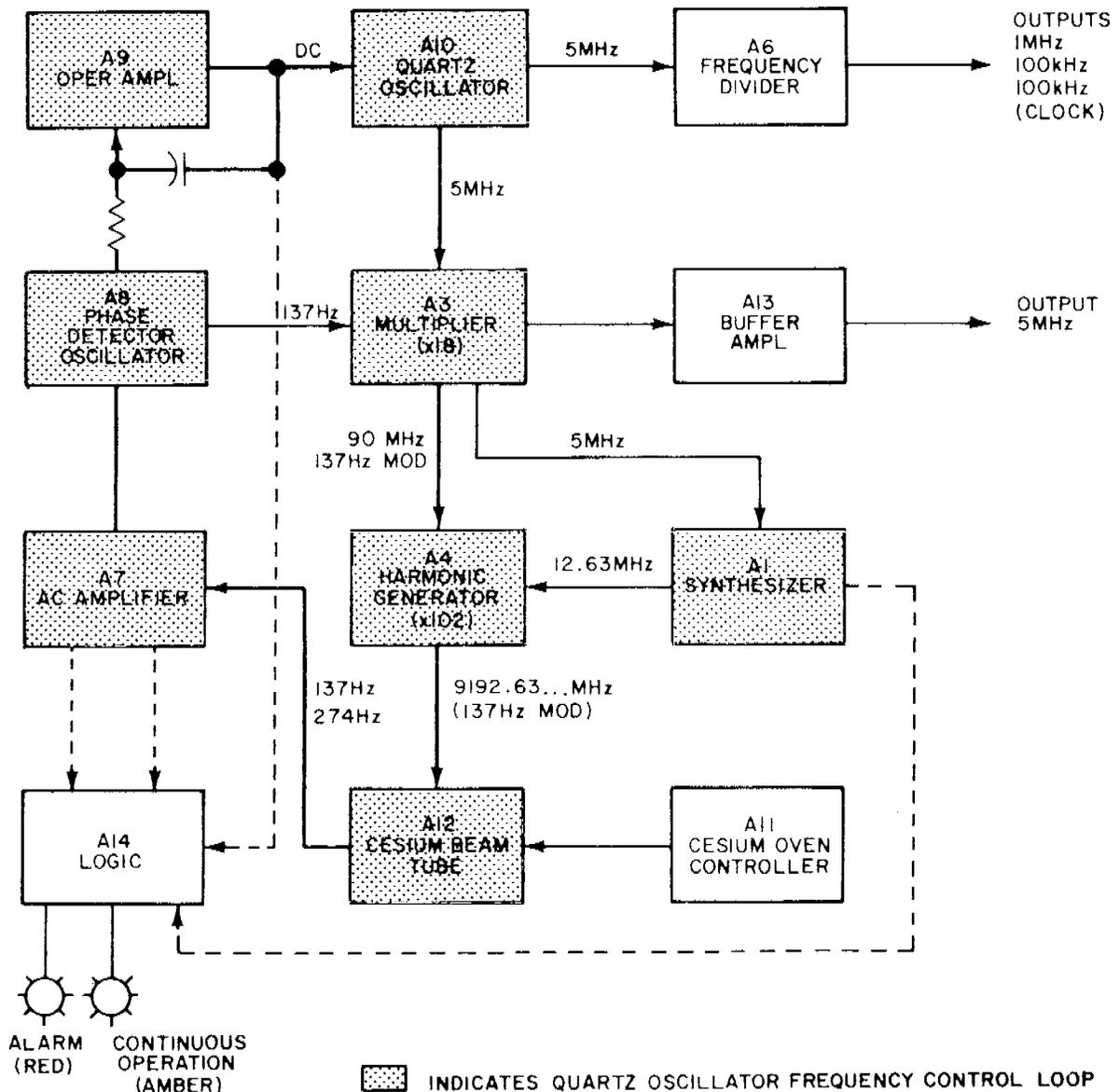

Fig. 1

CESIUM BEAM TUBE OPERATION

The schematic representation of the Cesium Beam Tube in Fig. 2 delineates the internal components and the cesium beam trajectory. Cesium atoms effuse from the oven source and are formed into a ribbon-like beam by a collimator. The beam passes through inhomogenous magnetic field of the first state selector magnet, the "A" magnet. The force experienced by a particular atom depends upon its effective magnetic moment hence upon its energy state, and also upon the gradient of the field; thus, atoms are selectively deflected into the interaction cavity. Two fields are present in this cavity, the "C" field and the microwave field resulting from multiplication and synthesis from the quartz oscillator. The presence of the C field, a steady-state, low level field, causes the desired separation to exist in the cesium atom's energy levels. The magnetic component of the injected microwave field interacts with the atoms. If the frequency is at the transition frequency, 9192+ MHz, then atoms absorb energy from the injected microwave field and flop to the other transition energy state. Since their effective magnetic moment is thereby reversed in its direction, a second state selector magnet, the "B" magnet, can selectively deflect flopped atoms to the detector. This detector, a hot wire ionizer, is a heated tantalum ribbon upon which the cesium atoms are ionized and then evaporated. The cesium ions pass through a mass spectrometer. The function of the mass spectrometer is to remove common contaminants such as potassium that might cause noise bursts that could overload the AC Amplifier in the frequency standard and cause loss of lock. The ions that pass through the mass spectrometer are accelerated into a multistage electron multiplier, where the ion current is converted to an electron current and amplified. The output current of the electron multiplier is carried by a coaxial cable to the signal processing electronics.
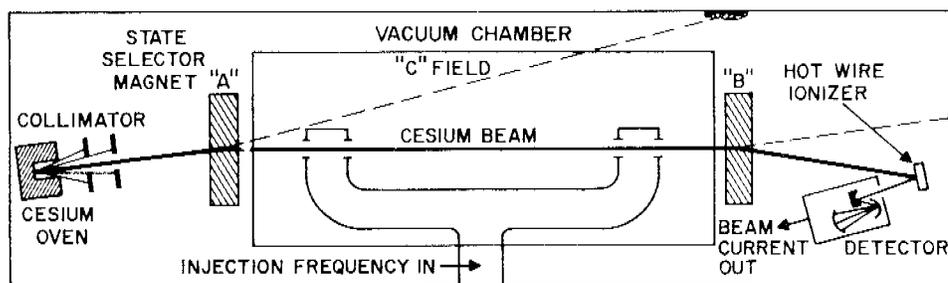

Fig. 2

The cavity is of the Ramsey type, with two interaction regions. The entire system is evacuated and is magnetically shielded.

BEAM TUBE DISCRIMINATOR ACTION

The cesium beam tube, in a simplified sense, is a passive device of extremely high Q that acts like a bandpass filter which by means of discriminator action provides an error signal to correct the phase of a quartz oscillator. Fig. 3 depicts the discriminator action. When the injected microwave signal is matched to the cesium atom transition frequency only the second harmonic component of the phase modulated signal appears in the beam current output. When the injected signal lies above or below the desired value, both the fundamental and the 2nd harmonic are outputted from the beam tube, with the fundamental (error signal) containing both phase and magnitude information used to control the quartz oscillator.
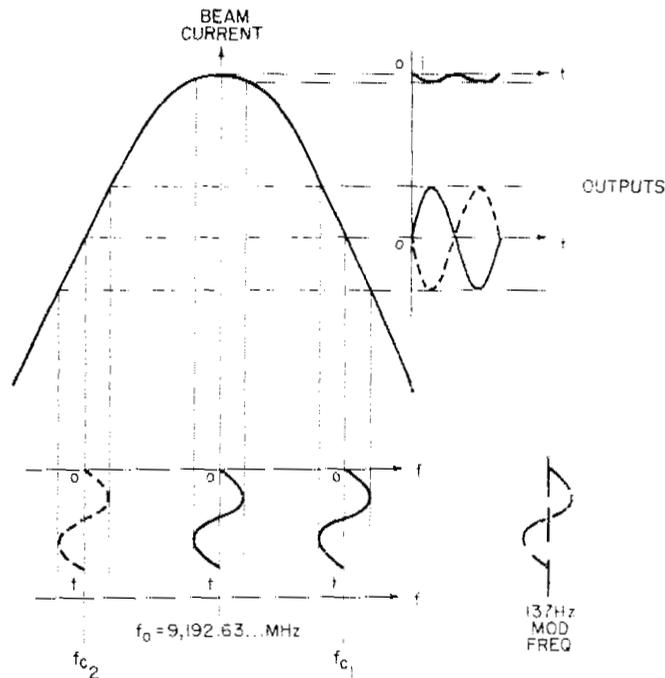

Fig. 3

ENERGY LEVELS

At zero magnetic field there are only two energy levels in which a neutral cesium atom can exist. However, upon application of a small

magnetic field (C Field) these two levels are split into 16 hyperfine levels, the higher energy (F=4) group into nine and the lower energy (F=3) group into seven. Figure 4 plots the hyperfine energy level subsets versus magnetic C Field strength. The dotted vertical line is representative of the typical C field setting of 60 milligauss. This value was chosen so that the field - independent transition; F=3, M_f=0 to F=4, M_f=0, is utilized.
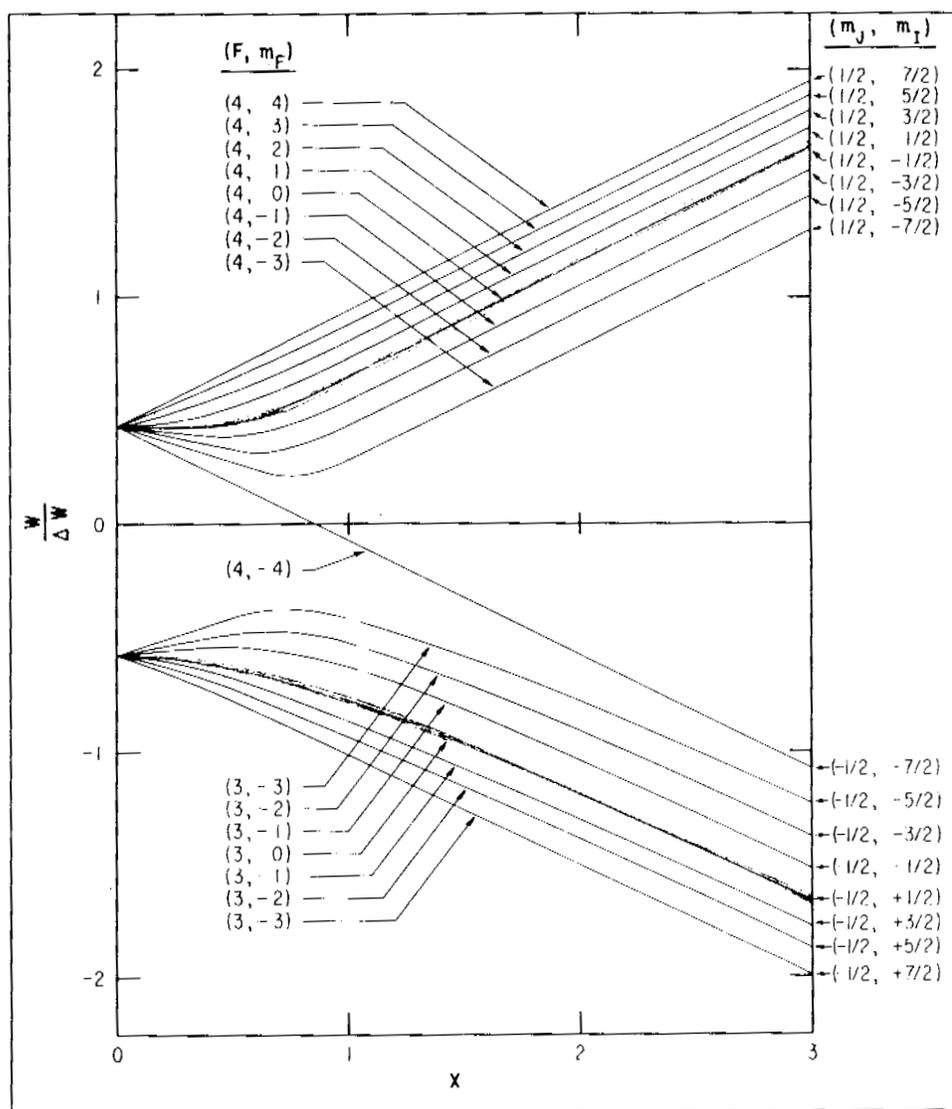

Fig. 4

C FIELD SETTING

The setting of the magnetic C Field is accomplished by applying the appropriate Zeeman frequency (42. 82 KHz for setting the Al Rate) to the harmonic generator which in turn excites the microwave cavity in the Cesium Standard. Figure 5 shows the beam tube output (Beam I) as a function of the microwave frequency. The center pedestal, labeled 0. 0) represents the desired energy level transition. Each transition contains a family of curves (Ramsey Fingers) consisting of a central peak and symmetrical sub-central peaks. Illustrated above the 0, 0 transition (i.e., F=4, Mf=0 and F=3, Mf=0) is a family of Ramsey Curves (fingers). With a fixed Zeeman frequency input the families of Ramsey curves depicted in Fig. 5 can be obtained by ranging through the Cesium Standard's "C Field" control.
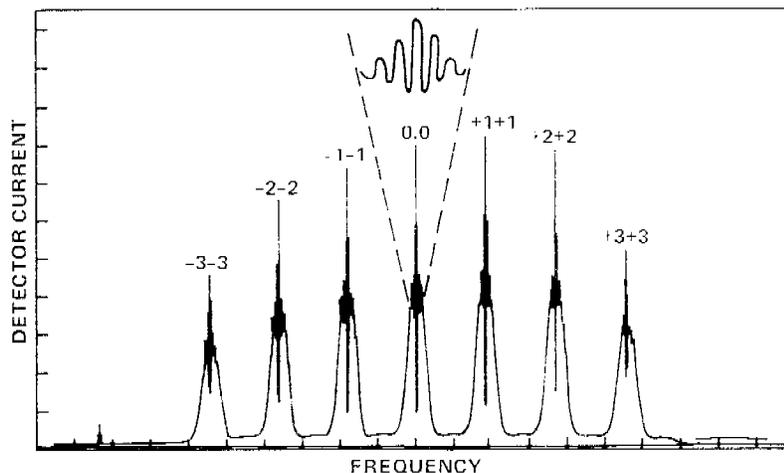
Fig. 5

ZEEMAN/C FIELD TEST SET

Fig. 6 is a block diagram of the test set used to demonstrate the effects of misadjusting the magnetic C Field. It consists of two cesiums, a test unit and a reference unit, from which the 5 MHz outputs are phase compared. The reference units's C Field has been correctly set and its output frequency verified to be within one part in ten to the twelfth of the Naval Observatory's master clock. The signal generator provides the Zeeman input, in this

case 42.82 KHz, for developing the Al rate in the unit under test. The frequency counter substantiates the correctness of the Zeeman Frequency.

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                          ┌─────────────┐
                          │  FREQUENCY  │
                          │   COUNTER   │
                          └─────────────┘
                                 │
                                 │
┌─────────────┐              ┌───┴─────────┐        ┌─────────────┐
│   SIGNAL    │  42.82 KHz   │   CESIUM    │        │   CESIUM    │
│  GENERATOR  ├─────────────▶│    STD.     │        │    STD.     │
│             │              │ (TEST UNIT) │        │ (REF. UNIT) │
└─────────────┘              └─────────────┘        └─────────────┘
                                    │                      │
                                    │                      │
                          5 MHz  ┌──┴──────────┐  5 MHz    │
                                 │   φ DET.     │◀──────────┘
                              ──▶│  RECORDER   │
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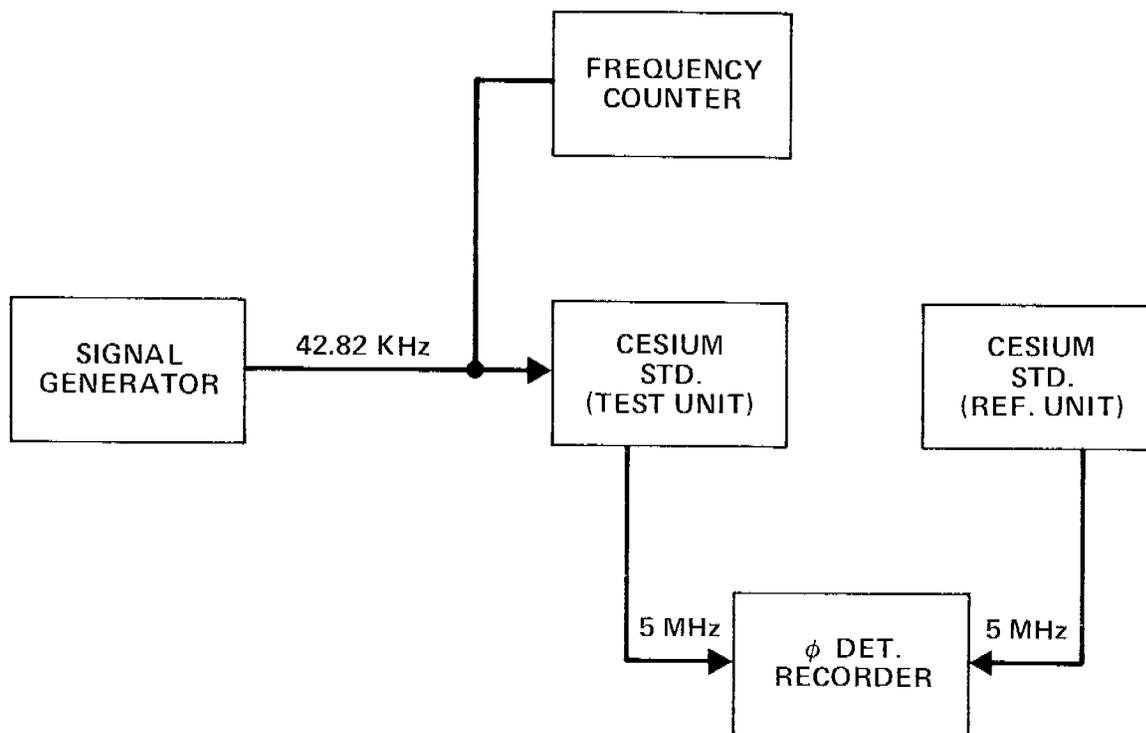
ZEEMAN/C FIELD TEST SET

Figure 6

THE DEMONSTRATION

On the Cesium Standard under test, set the mod switch to "OFF" and the mode switch to "OPEN". With the test set mentioned above and with the signal generator adjusted to the Al Zeeman rate of 1 volt RMS amplitude and interfaced to the "ZEEMAN IN" jack of the cesium under test, slowly rotate the ten turn "C Field" control while monitoring "Beam I". Start with the "C Field" potentiometer maximum clockwise and rotate the control slowly through its entire range. Record all Beam I peaks and their associated "C Field" control settings. Select the maximum "Beam I" "C Field" control setting and switch to "MOD ON" and to "MODE OPERATE". The alarm lamp should

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go out and upon depressing the "LOGIC RESET" button the "CONTINUOUS"
operation lamp should come on. NOTE: Selection of any Beam I peak,
central or sub-central, of any Ramsey family of curves, will result
in the "CONTINUOUS" operation lamp on, indicating normal operation.

ANALYSIS OF THE RESULTS

Figure 7 is a tabulation of the families of Ramsey fingers detected
for two Hewlett Packard Model 5061A Cesium Standards. The "Beam I"
their associated "C Field" values, the energy level transitions, the
frequency offsets of the sub-central to the central peaks, and the
maximum frequency difference (between the central peaks of the the
most widely displaced Ramsey families) are listed. By virtue of
the tabulation the following facts become evident: There is excellent
symmetry in both amplitude and frequency offset of the sub-central
peaks; the difference in amplitude between the central and the ad-
jacent sub-central peaks is small and suggest care in setting the
"C Field" to avoid aligning to a sub-central peak, a real possibility

| | ZEEMAN TRANSITION | Δf | BEAM I — C FIELD | | |
			HI SIDE	CENTER PK.	LO SIDE
SERIAL NO. 218	3,0 → 4,0	8×10^{-12}	40	50	40
			7.22	7.06	6.88
	3,1 → 4,1	3×10^{-12}	19	20	19
			4.72	4.66	4.60
	3,2 → 4,2	4×10^{-12}	35	42	35
			3.56	3.48	3.38
	3,3 → 4,3	3×10^{-12}	32	36	32.5
			2.34	2.28	2.22
SERIAL NO. 166	3,0 → 4,0	9×10^{-12}	47	50	47
			7.36	7.18	7.00
	3,1 → 4,1	4.5×10^{-12}	45	47.5	45.5
			3.53	3.44	3.37
	3,2 → 4,2	3×10^{-12}	42	44	42.5
			2.26	2.20	2.15

MAX. Δf BETWEEN CENTER PEAKS

SER. NO. 218 = 2.39×10^{-10}

SER. NO. 166 = 2.49×10^{-10}

FIGURE 7

of setting to an incorrect central peak because of the high Beam I values attainable, thus resulting in significant frequency offset error; and finally the correct frequency setting is defined by the two to one greater frequency offset between the sub-central peak and the central peak of the desired transition versus the Δ F of the undesired transitions. This latter fact provides verification of when you have selected the correct central peak and may be used when no other means of verification, such as portable clock, Loran-C or VLF phase comparisons are available. It is well to note, that by design, all Hewlett Packard Model 5061A Cesium Frequency Standards (Pre 1974), correct "C Field" settings always fall within 6.50 and 7.55 on the "C Field" control dial.

Figure 8 shows approximately 8 hours of phase ($\emptyset$) comparisons between the test unit serial number 166 and the reference unit for three different magnetic "C Field" settings. The first hour of the $\emptyset$ plot is representative of the worst case, where the C Field is set to the central peak resulting in the greatest frequency offset, followed by 4 hours of $\emptyset$ comparing with the C Field set to the adjacent sub-central peak of the desired transition and finally 3 hours of the 5 MHz data with the "C Field" set to the central peak of the desired transition.
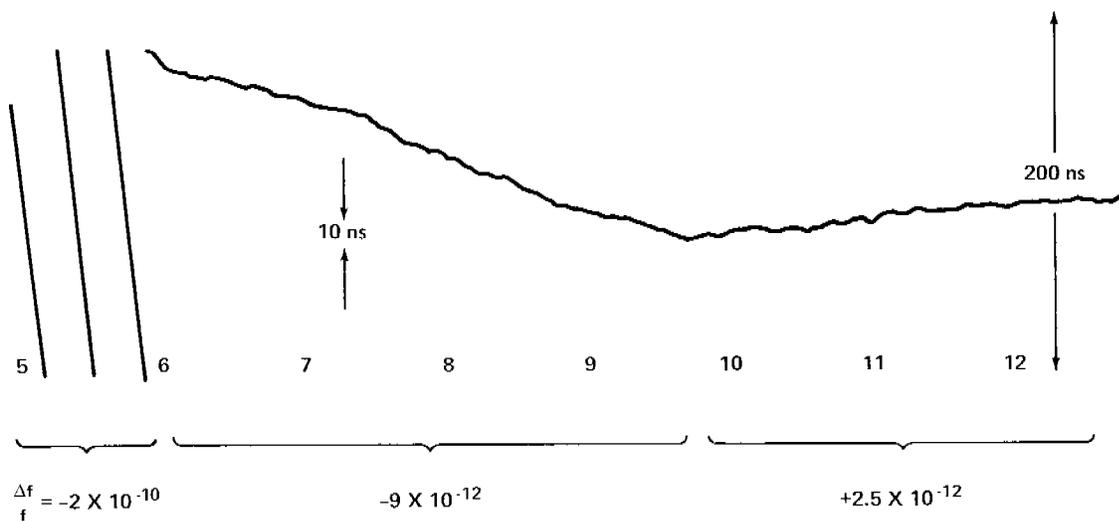

5 MHz ϕ PLOT

Fig. 8

In conclusion it should be emphasized that since 1974 the Hewlett Packard Model 5061A Cesium Standard, high performanc (004) version as well as the standard version, have a higher resolution "C Field" control with a much reduced range, only 2.5×10^{-11}, and therefore the magnetic "C Field" in these units can only be misadjusted to an adjacent sub-central peak of the correct energy level transition resulting in a maximum frequency offset error of 1×10^{-11}.

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QUESTION AND ANSWER PERIOD

DR. REDER:

(Comments not recorded due to remote microphone inter-
mittent operation) - Regarding problems of locking on.

MR. BEATY:

Jim Beaty, FAA NAPEC.

Perhaps I could share the benefit of some experience that
we had in Atlantic City. As noted, the central peak or the
proper peak, of the Ramsey tube is symmetrical for the types
of accuracies we are talking about in commercial clocks,
while the peaks below or above are slightly asymmetrical.
In fact, this is the basis for the logic that HP uses in
detecting the false peak. However, an added check would be
if one is setting the C field and then one has a synthesizer,
preferably, but even very carefully with a stable oscillator
and a counter, one can set up your 42.82 Zeeman frequency
and then center that very carefully and then if one changes
the Zeeman frequency by a plus or minus of 100 cycles, then
the decrease in beam I ought to be the same, if you are on
the symmetrical curve.

It is not the same when you are on one of the other peaks
and you have to readjust. We have used this very success-
fully. In fact, it is a good way to make sure that you
are right on top of the proper curve, in fact, because that
is rather insensitive. The panel meter is rather insensi-
tive to very, very small differences in beam I and if you
don't have an auxilliary meter there, you can just punch
up on your synthesizer, for instance, 42.92, 42.72, and
your beam I should decrease the same amount if you are
right on the center.