RUBIDIUM AND CESIUM FREQUENCY STANDARDS STATUS AND PERFORMANCE ON THE GPS PROGRAM

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INTRODUCTION

The evolution of the frequency standards on the GPS program started with the Block I concept validation program, beginning with a proposal program in 1973 and followed by the (GPS 1 through 8) prototype space vehicle contract in 1974. The full-scale developmental (GPS 9 through 11) models contracted in 1978 provided both navigation and nuclear detection capability. The production qual vehicle (GPS 12) was contracted in 1980, and the production vehicles (GPS 13 through 40) were contracted in 1982.

During the proposal phase of this program, the on-board frequency standards were considered the most critical item within the GPS navigational system for achieving user position accuracy. Therefore, a considerable amount of effort was devoted to the frequency standards. The initial GPS vehicles (GPS 1 through 3) incorporated three rubidium frequency standards, each with a backup mode, to minimize the risk to the GPS program on this critical item. This was achieved by operating a high performance VCXO without its rubidium reference. This design concept resulted in the redundancy potential of six frequency standards per vehicle. Later space vehicles, starting with GPS 4, included an additional cesium frequency standard, also with a backup VCXO mode. This extended redundancy was deemed necessary in lieu of the more conventional dual redundancy because if the rubidium loop failed, then the VCXO could be utilized as a backup device that would maintain frequency stability for a specific period of time, as required, to maintain navigational accuracy over the test area. The actual on-orbit GPS frequency standard operating history shown in Figure 1 illustrates the results of this hardware implementation.

As this clock program progressed, ten different models of the rubidium standards have evolved. The part numbers of the different models of each frequency standard are shown in Figure 1. The first rubidium standards on Navstars 1 and 2 accumulated a total of 44 months of operation with 6 failures, which necessitated switching to the backup modes (1978 through 1980). The backup mode operating time is 138 months and still counting. Navstar 1 was officially declared inoperable on December 1985 (7.7 years). Navstar 2 has two clocks with an operable backup mode, but no navigational or Kalman data is taken; just the power levels of L_1 and L_2 are monitored. The last 67 months of GPS rubidium clock operation on Navstars 4, 6, and 8 have seen one failure and three anomalies. The on-orbit chronology of events on the cesium frequency standards were very similar to the rubidium frequency standards. After an initial power supply problem, the preproduction models (PPM) have a total of 87 months of operation for three units with only one failure (depletion of cesium).

All GPS production vehicles, starting with GPS 0013, will include two cesium frequency standards and two rubidium frequency standards, each still with a backup VCXO mode.

ON-ORBIT PERFORMANCE

The operating summary and life history of the various design types of rubidium frequency standards are shown in Table 1, and the cesium frequency standards are shown in Table 2. In order to acquire the exact performance characteristics of the frequency standards, a direct monitoring point would have to be attached to its output. Since this is not directly monitored, the performance evaluation is a combination of the frequency standard stability plus other outside effects, such as atmospheric effects, temperature coefficients, ephemeric unknowns, and other factors that are fed into the Kalman filter equations. Table 3 lists two parameters that come closest to directly evaluating the operating characteristics of the frequency standards. Both parameters are read off of the Kalman filter estimate residual. The motion, in sec/sec/day, is the difference between the maximum and minimum values of Kalman data, which is a relative value. The final offset value, in nanosec/sec, is the final value of Kalman data at the end of each day, which is an absolute value. There are four cesiums and two rubidiums operating in the primary mode on the six experimental satellites. On the other two satellites (Navstars 2 and 4), the rubidium standards are operating in the backup mode.

RFS ORBITAL ANOMALIES

The on-orbit operational data of GPS rubidium frequency standards started with Navstar 1 in March 1978, followed by Navstar 2 in May 1978. The three major types of problems that have been experienced include (1) power supply transformer failures, (2) too low a fill in the rubidium lamps, and (3) an oscillation in the VCXO heater control, and all have been eliminated starting with Dash 3 (XMFR problem) and Dash 4 (Rb fill) (Reference 1).

The effectiveness of the transformer change can be seen by noting the operating history of the Dash 3 and subsequent standards. Clock 1 on Navstar 3 has been operating for 94 months and Clock 3 on Navstar 4 for 58 months (RB depletion on October 27, 1986). The rubidium "underfill" problem has not reappeared after Dash 4 frequency standards.

Another anomaly has appeared quite regularly on Navstar 6, which involves digital tuning word shifts. Why this has not occurred with more regularity on other standards is not understood. A possible cause could be static discharge on the spacecraft cables to the clock. In the nine months of operation, August 1984 through May 1985, about 25 disturbances occurred on the clock in position No. 3. Another Rb frequency standard, in position No. 1 with shorter coaxial cable lengths to the command decoder, was switched on May 1985. There have been no offsets since. To solve the problem, a newly designed digital tuning circuit has been incorporated in Dash 11 clocks. This was to desensitize the circuitry to transient spikes and require four good clock pulses before executing the tuning word command.

The orbital temperature variation of the spacecraft and, in particular, of the rubidium clocks has affected the frequency output of the clocks. With a temperature coefficient of the clocks being $\pm 1 \times 10^{-12}/°C$, a temperature change of 2 to 3 °C per orbit would change the frequency accordingly. Therefore, a temperature controller was introduced under each rubidium clock on Navstar 8 and on each subsequent Navstar vehicle. The performance of the rubidium standard on Navstar 8 with its temperature controller (± 0.1°C) has been comparable to the cesium standards. The stability values were high parts in 10^{14}, one day averaging time. In May 1985 (the 34th month of operation), the short-term stability, <10 sec, went out of specification but not the long-term stability, >1000 sec. Only the ground stations monitoring or utilizing the short-term data were aware of the instability problem. The Rb standard was commanded to the backup mode in order to isolate the problem (Rb loop or VCXO loop). After two days, the Rb standard was turned off and the cesium standard was commanded on. No conclusive evidence to date has been found to determine the cause of this anomaly.

The effectiveness of the backup mode concept and the design changes to the standards can be seen by noting that the standards on the first six satellites have more than fulfilled their 5-year, experimental, lifetime specification.

CESIUM ON-ORBIT ANOMALIES

As previously stated, the first GPS satellite to operate a cesium frequency standard, in addition to three rubidium standards, was Navstar 4. The backup VCXO mode of this clock is still operational after the cesium-half of the power supply failed (Reference 1).

Numerous design changes to the PPM were made, including new brazing procedures on the Cs tube and improved leak testing of the oven assembly. The corrective measures in the production models were to increase the amount of cesium fill from 1.0 gram to 1.5 grams and to provide stricter quality control and inspection points. The effectiveness of these changes has been verified by on-orbit data on Navstars 8, 9, and 10. Remember that Navstar 11 has a cesium PPM operating without the latest design improvements. Table 2 is a summary of the operating history of these various design modifications of the cesium clock.

The unused cesium standard on Navstar 8 has an interesting history because of the first trial run of the temperature controller for the rubidium clock. It has been in orbit for 34 months without being used. Turn-on occurred 7 months ago with no ill effects of 34 months of on-orbit storage, except for two ion-pump operations for 10 minutes each.

The life testing in progress at the Naval Research Laboratory (NRL) adds to our confidence of on-orbit operation. These tests include (1) two tubes still with 1.0 grams of cesium, which were fabricated with improvements (46 months of continuous operating time on each tube with no failures) and (2) a PPM for 54 months with no problems.

SCHEDULES AND FUTURE PROGRAM

The last of the Block I satellites, Navstar 11, was launched on October 8, 1985. This was a qualification space vehicle for Block I space vehicles and secondary payloads. The ten spacecraft are situated in two orbital planes, four in the 120 deg plane and six in the 240 deg plane. Larger Block II GPS satellites with additional payloads were designed to be carried aboard the Space Shuttle and launched into orbit by PAM-D booster rockets. The fully operational constellation will consist of 18 operational spacecraft (three spacecrafts separated by 120 deg in each plane of which there will be six different orbital planes separated by 60 deg) plus three on-orbit spares. GPS 13 through GPS 21 are planned to be launched from expendable launch vehicles commencing in mid-1988. GPS 22 and GPS 23 will be called GPS 1 and GPS 2, respectively, by NASA and will both be launched approximately mid-1989 from the Columbia as a dual launch. Three months later, GPS 3 and GPS 4 will be launched from the Columbia with GPS 5 in 1990. The last two operational satellites to fill the constellation, GPS 7 and GPS 8, are targeted to be launched in 1991. Starting with GPS 7 and GPS 8, the tentative plans are to replace one of the primary cesium standards with one of the second source cesium standard being developed by Kernco and Frequency Electronics, Inc., under the direction of the NRL.

Other potential plans dealing with GPS (but not part of the GPS constellation) will be utilizing a refurbished GPS 12 vehicle for the purpose of experiments with advanced frequency standards. The experimental objectives would be to demonstrate that compact hydrogen-maser and other advanced atomic clock technology will operate in space for extended periods of time, and to separate orbital position and velocity errors from clock errors in space system.

CONCLUSION

The validation of the approach taken on the GPS program to have frequency standards with both a primary and secondary mode of operation is very apparent. A total (all clocks) of 469 months (39 years) of on-orbit time has accumulated in the primary mode of operation and 610 months (50.8 years), including the backup mode of operation.

On-orbit performance data substantiates a very effective development effort. Corrective actions eliminated early rubidium and cesium problems. Dash 3 rubidium standards corrected the transformer and VCXO oscillation problems. The Dash 4 units corrected the lamp problems. The same results are apparent in the cesium frequency standards. The corrective actions taken associated with the power supply problem have not reoccurred in any of the PPM or -0001 units. There are sufficient on-orbit data to verify the corrective measures taken to eliminate early depletion of the cesium, plus more than 100 months of laboratory data have accumulated at NRL that demonstrates the effectiveness of the various changes on the production tubes.

REFERENCES

1. Ringer, D., H. Bethke, and M. Van Melle. Rubidium and Cesium Frequency Standard Status and Performance on the GPS Program. Presented at the 16th Annual PTTI Meeting (November 27-29 1984).

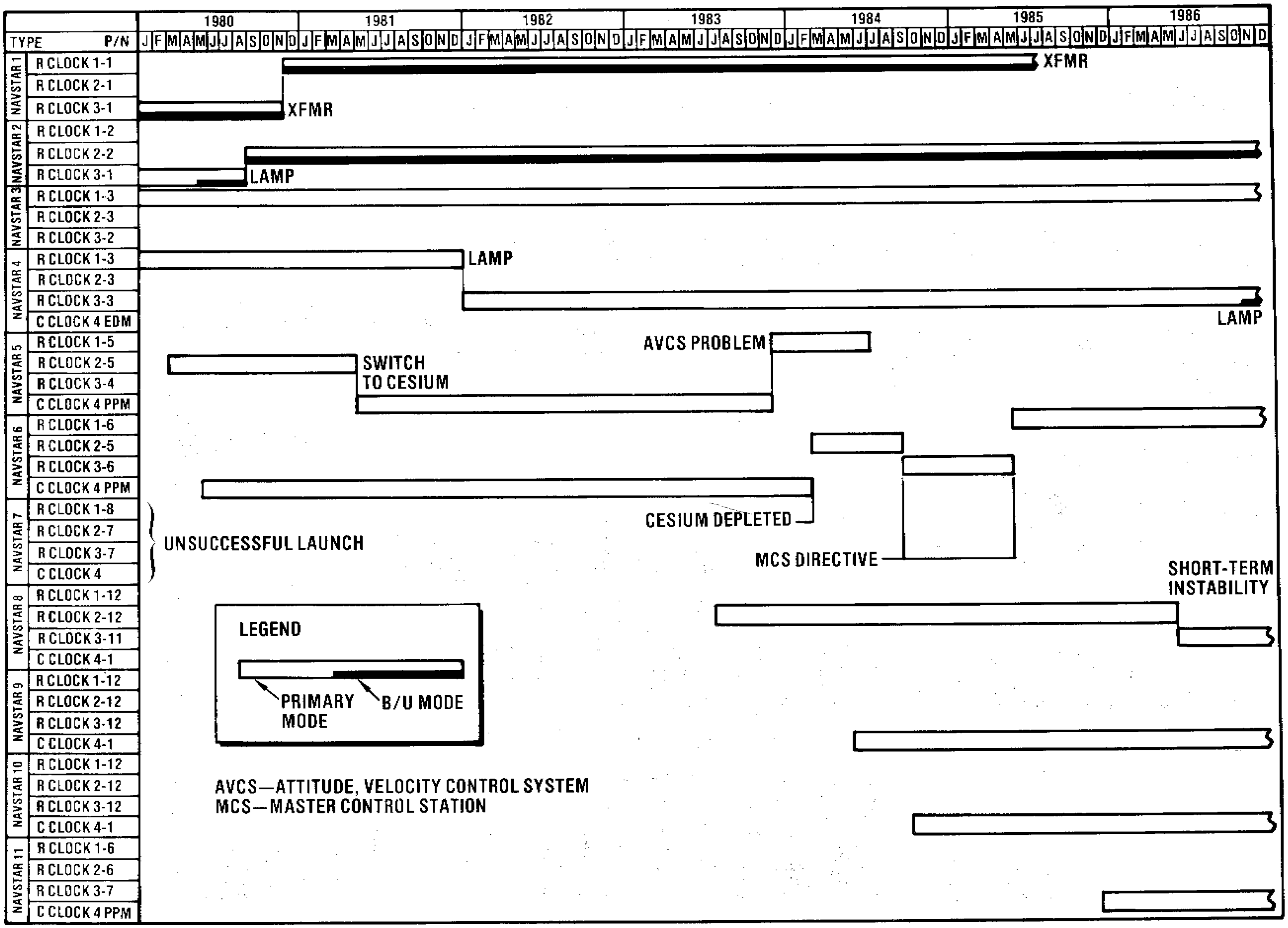

Figure 1. Navstar Clock Operating History

Table 1. GPS Rubidium Frequency Standard Operating Summary (Primary Mode)

Navstar	P/N	Months of Operation 1978	1979	1980	1981	1982	1983	1984	1985	1986	Total (mo)	Failures	Failure Mode	Comments
1	-0001	10	12	B/U	B/U	B/U	B/U	B/U	B/U	0	22	3	Lamps, XFMR	B/U—backup mode 61 mo 7/85 officially off
2	-0001 -0002	6	12	4	B/U	B/U	B/U	B/U	B/U	B/U	22	3	Lamps, XFMR	Low frequency oscillation (B/U 71 mo) Nonoperational
Total		16	24	4	0	0	0	0	0	0	44	6		
NEW POWER SUPPLY XFMR DESIGN (-0003 AND SUBSEQUENT)														
3	-0003	2	12	12	12	12	12	12	12	11	97	1	Frequency offset	Second Rb clock on for 94 mo (7.8 yr)
4	-0003	0	12	12	12	12	12	12	12	10/B/U	94	3	Lamps	B/U still operational, same Rb on for 5 yr
Total		2	24	24	24	24	24	24	24	21	191	4		
RUBIDIUM LAMP CHANGE (-0004 AND SUBSEQUENT)														
5	-0004 -0005	0	0	10	4	Cs Op	Cs Op	3	0	0	17	0	None	AVSC problem Cs—cesium clock
6	-0005 -0006	0	0	Cs Op	Cs Op	Cs Op	Cs Op	11	12	11	34	0	Drift*, frequency shifts*	Drift out of spec, $> 10^{-12}$/day; Digital tuning word shifts
8	-0011 -0012	0	0	0	0	0	4	12	12	5	33	0	VCXO*	Short-term instability, < 10 sec; Cs on 5/15/86
Total		0	0	10	4	0	4	26	24	16	84	0	None	

*Anomalies

Table 2. GPS Cesium Frequency Standard Operating Summary

Navstar	P/N	Months of Operation							Total (mo)	Failures	Failure Mode	Comments
		1980	1981	1982	1983	1984	1985	1986				
4	EDM	0	0	0	0	0	0	0	0	1	High voltage power supply	Backup (VCXO) mode still operational
5	PPM	0	7	12	11	0	0	0	30	0		AVCS problem
6	PPM	7	12	12	12	1	0	0	44	1	Depletion of Cs	Backup (VCXO) mode still operational
8	-0001				0	0	0	7	7	0		Turned on after being off for 34 mo
9	-0001					6	12	11	29	0		
10	-0001					3	12	11	26	0		
11	PPM						2	11	13	0		
Total		7	19	24	23	10	26	40	149	2		Months of operation/ failure 149/2 = 74.5

Table 3. GPS (Clock) Performance Characteristics

Navstar	Motion (sec/sec/day)	Final Offset (nsec/sec)
3 Rb	10^{-12}	0.015
4 Rb (B/U)	10^{-10}	0.1
6 Rb	10^{-12} to 10^{-13}	0.025
8 Cs	1-2 X 10^{-13}	0.0055
Rb	5 X 10^{-13}	0.015
9 Cs	1-3 X 10^{-13}	0.003
10 Cs	5 X 10^{-13}	0.005
11 Cs	3 X 10^{-13}	0.0005

QUESTIONS AND ANSWERS

MARK WEISS, NATIONAL BUREAU OF STANDARDS: There is no way to launch another satellite before January of 1989?

MR. VAN MELLE: That's right. We have no expendable boosters.We got caught short by trying to rely too much on the Shuttle as a work horse. We are finding out that Shuttle is really not a work horse for all satellites. It takes about 21 months from go-ahead to delivery of the boosters for one thing, and we don't have any boosters setting around. We are depending on Atlas-Centaur, the Stretched Delta or the Titan 34D to put up our GPS'S. In fact the GPS vibration specifications on the Shuttle are worse than on the boosters, so we don't really have to change any thing on the clock specifications or any of the payloads, luckily.

MR. WEISS: So, what is the backup mode? I don't understand that. If something fails, is there something that could be done on some of the ones that are up there?

MR. VAN MELLE: Oh yes, the backup modes for the rubidium and the cesiums are the fact that you have a VCXO, a crystal VCXO, and instead of relying on the rubidium loop to update the VCXO all the time, when the rubidium loop fails, the VCXO will just be free-running. The VCXO that is in the rubidium is made by FEI and has very good characteristics. The backup VCXO for the cesium is made by FTS, who also makes the primary standard.

MR. WEISS: Are you talking quartz?

MR. VAN MELLE: Yes. They are parts in ten to the tenth instead of parts in ten to the thirteenth. Probably when one of the primary standards goes down, they will switch to the next primary etc. and then just forget it because of the loss in performance with the backup mode. Probably the rubidium or cesium clocks made for the next vehicles will not have a backup mode. We would probably never use it because it is so bad for navigational purposes. We would just switch another whole satellite in its place. One other question that was raised for NAVSTAR 3 - remember that the lifetime is only five years on those and it is approaching 8 years since launch. I admit that the solar panels are getting very inefficient and every six months this NAVSTAR goes through an eclipse and there is no solar power and you have to go to the battery. The battery is also failing on NAVSTAR 3 and 4. On 4 we don't worry too much, but 3 has a beautiful clock, in fact it has a rubidium that has never been turned on. We are going to have to power down this spacecraft when it goes through these eclipse periods. I think that we have another year or year and a half, or two and possibly three eclipses before we lose the whole spacecraft because of age. Maybe 4 has another year. The spacecraft are getting very old.

BERNARD SERENE, THE EUROPEAN SPACE AGENCY: You reported on an electrostatic problem which upset the clocks. Has this problem been correlated with other problems on board? Do you have any information on that?

MR. VAN MELLE: No, I don't. We have a good handle on the electrostatic discharge problem now, but remember that these problems occurred on a real old spacecraft which was launched in 1978. Conceptually, we think that the reason is that we switched to another clock and it had different cable lengths to the dual command decoder. By switching clocks, and getting different cable lengths the problem went away. We assume that it was an electrostatic discharge problem, but we also changed the circuitry inside the clock to accept four good clock pulses before putting the command in. We thought that that was the problem.

MR. SERENE: We tried to look at the problem also. Most of the time when we don't know the source of the problem, it is attributed to electrostatic discharge. This is garbage!

MR. VAN MELLE: It's like black magic. It is either nuclear radiation or EMC problems.

QUESTIONS AND ANSWERS

K. UGLOW, ELECTRONICS RESEARCH: I remember from some years ago that the phase velocity in the ionosphere is changed in the opposite direction form the group velocity. I understand that APL was going to do some tricks with this to improve the data from the Transit type of Satellites with the PRN equipment. Is that of some use in this work?

MR. VAN MELLE: I failed to mention that when I take the difference of pseudo-ranges, it is the difference between the L2 pseudo-range and the L1 pseudo-range, the lower frequency minus the higher frequency pseudo-range. When calculating the accumulated delta range differences, I reverse the order of the data, the L1 carrier tracking minus the L2 carrier tracking, so that the shape of the curve, on the average, is the same. The phase velocity increase and the group velocity retardation are exactly the same and of opposite polarity, as shown by this agreement.

MR. BUISSON: We do similar work to this and I wondered how you decided that a seventeenth order polynomial was the best as opposed to a sixteenth or fifteenth.

MR. VAN MELLE: I run it for a nineteenth order polynomial, an eighteenth, a seventeenth, a sixteenth, a fifteenth, and so on. Then I compare the residuals for each of the polynomials. The residuals decrease as the order of the polynomial increases, but there is a knee in the curve beyond which very little improvement is seen. For this particular example, the knee occurs pretty clearly at the seventeenth order polynomial.

MR. ELLETT, DMA representative at JPO: With respect to the multipath that you show, the magnitudes were fairly low. Can you give some indication as to the elevation angle?

MR. VAN MELLE: I have never really tried to correlate the data that you see with the trajectory itself. It probably was low because the dominant effect was at the beginning of the pass so it probably was at a low elevation angle. I have never actually examined it.

MR. ELLETT: The only reason that I bring this up is that Allan Evans at NSWC has mentioned some techniques for identifying multipath also. Of course, he was using a TI 4100 in a NSWC environment. I believe that he found larger values for multipath, but they may have been more locally related than yours.

MR. VAN MELLE: What I am talking about regarding multipath is at the operational control system monitoring stations. To begin with, they put the antennas in a location which would be a good location from the point of view of multipath. For example, early in the program a monitoring station was set up on the roof of the IBM building in Gaithersburg. There, the multipath effect was a lot worse because it was a temporary, check-out kind of situation. The point is that at the monitoring stations we do apparently put the antennas in a good location. If you really like multipath, you can find a way of setting up the antennas that will make it show up.