Utilization of an NNSS Receiver in the Explosion Seismic Experiments on the Prince Olav Coast, East Antarctica 1. Recovered UTC

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東南極，プリンスオラフ海岸で行われた爆破地震実験における航行衛星の利用 1. 世界協定時の復元

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要旨: 商用の 400 MHz 1 波の NNSS 受信器を改造し，世界協定時を復元して，それと同期した 1 秒 1 パルス割合の BCD パルスを発生できるようにした．この受信器の性能試験を行った結果±5 ms の総合的な精度で標準時計が得られることがわかった．この受信器を用いた時刻較正によって，第21次南極地域観測隊がプリンスオラフ海岸で行った 3 回の爆破実験のショットタイムが 5 ms 精度で決められたほか，雪原の劣悪な作業環境下でも，実験に用いられた合計 30台の時計の時刻あわせを0. 01秒以内で行うことができた.

Abstract: A commercial 400 MHz NNSS receiver was altered to recover and generate UTC synchronized BCD pulses of one pulse per second. The altered NNSS receiver was tested and ascertained that it could generate UTC within an overall accuracy of ±5 ms in the antarctic region. By the aid of this NNSS receiver, shot times of explosion seismic experiments, which were made by the 21st Japanese Antarctic Research Expedition on the Prince Olav Coast, East Antarctica, could be determined within an overall accuracy of 5 ms. Timing of a total of 30 clocks in the experiments could also be made within an accuracy of 0.01 s under the bad operational conditions on a snow field.

1. Introduction

The 21st Japanese Antarctic Research Expedition (JARE-21), led by Dr. S. KAWAGUCHI, made several explosion seismic experiments on the Prince Olav Coast, East Antarctica in 1980–1981. In order to obtain a profile of about 300 km, three parties installed 27 temporary sensors and the corresponding DAR (Direct Analog Recording) recorders by taking partial charge of about 100 km (ITO *et al.*, 1981). Each party had its own master clock in order to calibrate the installed local clock in the DAR recorder, and so the timing of the three master clocks was required.

The receiving signals of the standard frequency waves, for example, JJY at 10 MHz at Syowa Station (hereafter referred to as SYO, the location of which

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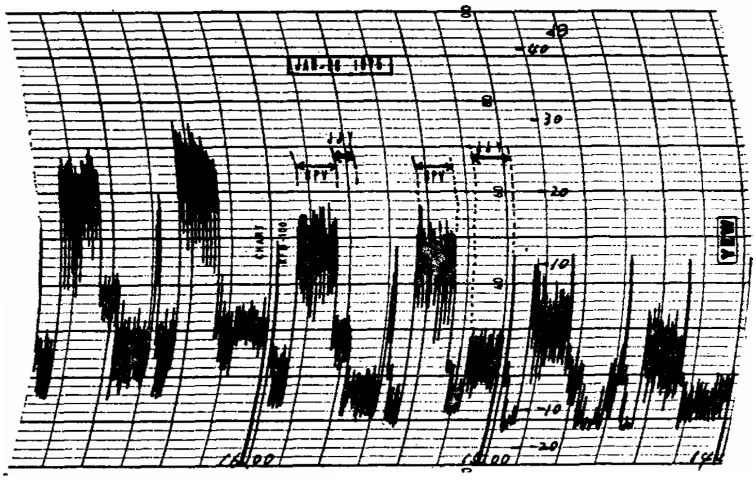

Fig. 1. An example of the record of standard frequency waves received with the narrow band receiver at Syowa Station, redrawn from SUGIUCHI *et al. (1979).*

is approximately 69°00′S and 39°35′E), are frequently overlapped by those of other standard frequency waves from Shanghai (BPV) and/or Hawaii (WWVH) as illustrated in Fig. 1. The receiving strength of standard frequency waves has been found also to be influenced by the state of ionosphere such as auroral phenomena (*e.g.* SUGIUCHI *et al.*, 1979). Receiving of standard frequency waves in the antarctic region also requires a large antenna and a sophisticated receiver, which was not practical in the field operation by a snow car. Calibrations of the three master clocks had to be made by another standard time base.

Utilization of satellites for obtaining a standard time base has made a remarkable progress in the last ten years. For example, GŌES (Geostationary Operational Environmental Satellite) receiver can provide UTC (Universal Time Co-ordinate) within the accuracy of 20 μs after the correction of path delays as

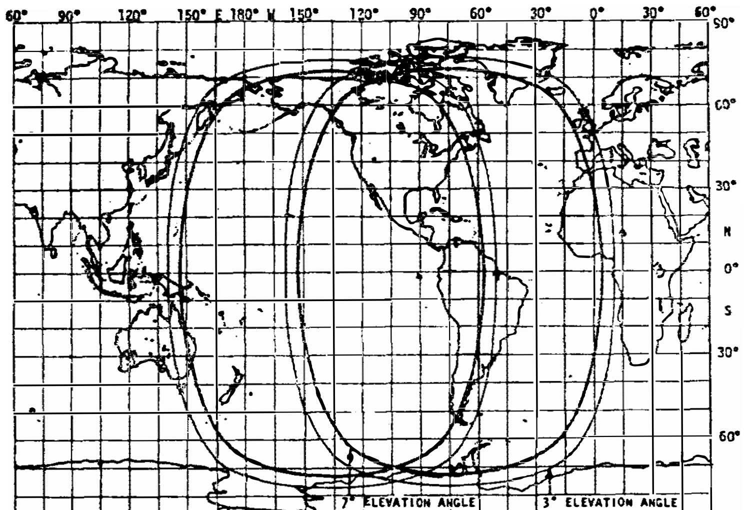

Fig. 2. The coverage of the GŌES satellites, redrawn from TIME AND FREQUENCY SERVICES SECTION *(1978).*

explained in the publications by TIME AND FREQUENCY SERVICES SECTION (1978). However, GŌES is located 36000 km above the equator and it cannot shoot most of the polar regions as illustrated in Fig. 2.

2. NNSS

The Navy Navigation Satellite System (hereafter referred to as NNSS) is an all-weather and world-wide positioning system which has been used commercially since 1968. NNSS had five satellites in use in 1980, the code numbers of which were 30110, 30130, 30140, 30190 and 30200, respectively. The NNSS satellite has a polar orbit of nearly 90 degrees inclination angle, the semi-major axis of about 7400 km and the period of about 106 min, as schematically illustrated in Fig. 3a. The longitudes of the ascending node of the five satellites were so distributed that they could give as many chances for positioning as possible. Since the detailed characteristics of NNSS and the receiver are described in many textbooks (*e.g.* KIMURA, 1977), only broadcasted information is reproduced here.

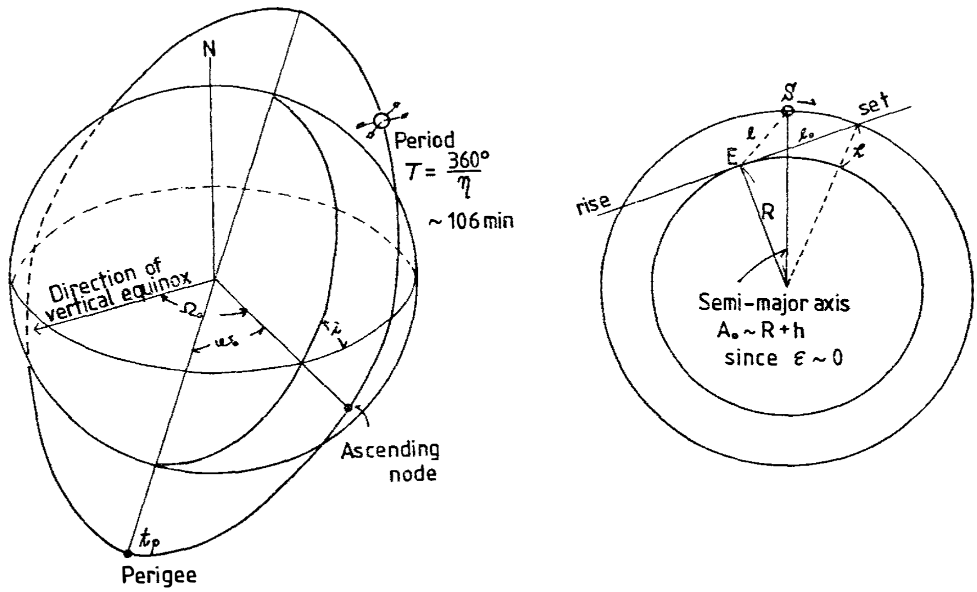

Fig. 3a. Schematic orbit of an NNSS satellite.

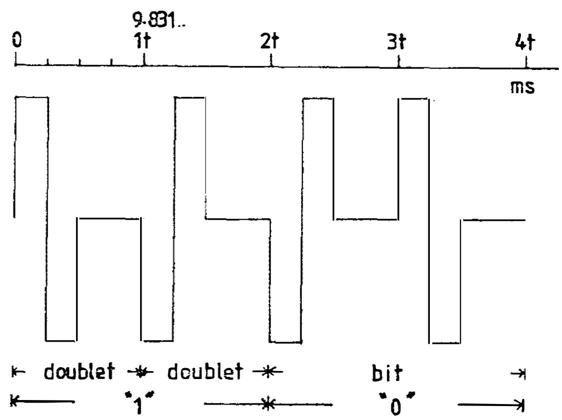

Fig. 3b. Binary digit "1" and "0" from NNSS.

LINE NUMBER	GROUP A					GROUP B		
1	BEEPER	4	5	6	7	T-6		VARIABLE DATA
2	9	10	11	12	13	T-4		
3	15	16	17	18	19	T-2		
4	21	22	23	24	25	T		
5	27	28	29	30	31	T+2		
6	33	34	35	36	37	T+4		
7	39	40	41	42	43	T+6		
8	45	46	47	48	49	T+8		
9	51	52	53	54	55	t_p		FIXED DATA
10	57	58	59	60	61	η		
11	63	64	65	66	67	ω_0		
12	69	70	71	72	73	$\dot{\omega}$		
13	75	76	77	78	79	ϵ		
14	81	82	83	84	85	A_0		
15	87	88	89	90	91	Ω_0		
16	93	94	95	96	97	$\dot{\Omega}$		
17	99	100	101	102	103	C_i		
18	105	106	107	108	109	A_G		
19	111	112	113	114	115	LAST INJ		
20	117	118	119	120	121	SAT ID		
21	123	124	125	126	127	S_i		
22	129	130	131	132	133	$\Delta\tau_S$		
23	135	136	137	138	139	ZERO		INJECTION
24	141	142	143	144	145	ZERO		
25	147	148	149	150	151	ZERO		
26	153	154	155	156	+19	1	2	TIMING MARK

Fig. 4. The format of transmitted data, redrawn from BRUNELL (1980). The meaning of the symbols is inferred from Fig. 3a. By demodulating the broadcasted bits, the following information can be obtained against, for example, 30190 fixed at 1940 UT, August 13, 1980 at SYO. t_p=848.1167 min, η=+3.3673149 deg/min, ω_0=+234.2031 deg, $\dot{\omega}$=+0.0020852 deg/min, ε=+0.016745, A_0=+7461.73 km, Ω_0=+273.9064 deg, $\dot{\Omega}$=+0.-0000102 deg/min, Ci=−0.002555, A_G=+174.1913 deg, Si=+0.999997.

The NNSS satellite has a frequency-stabilized oscillator. Coherent waves of 399.968 MHz and 149.988 MHz with 8/3 frequency ratio are made from the oscillator and transmitted from the satellite. The above waves are phase-modulated to give the signal waveform which is called "doublet". The combination of two doublets expresses "0" or "1", as illustrated in Fig. 3b. One bit has 19.6625 ms length and 157 words of 6103 bits are stored in a two-minutes frame (Fig. 4). Since the third word has the different phase-modulated waveform (BEEPER in Fig. 4), the rising of the third word can be recognized as the timing mark. The absolute accuracy of the timing mark is guaranteed by the Naval Astronomical Observatory, Washington D.C., USA, by referring to an atomic clock within ±200 μs against UTC, together with the 10 μs interval accuracy of the two-minutes frame. If time codes which are synchronizing with a certain recovered time mark of the NNSS satellite can be generated, they can give an accurate time base at any desired moment and place in the world.

3. Experiments

Generation of UTC-synchronized slow rate BCD (Binary Coded Decimal) pulses of one pulse per second (hereafter referred to as recovered UTC) is performed by altering a commercial 400 MHz NNSS receiver for navigation, JLE3300, Japan Radio Company. The flow chart in Fig. 5 (altered from DOVE, 1978)

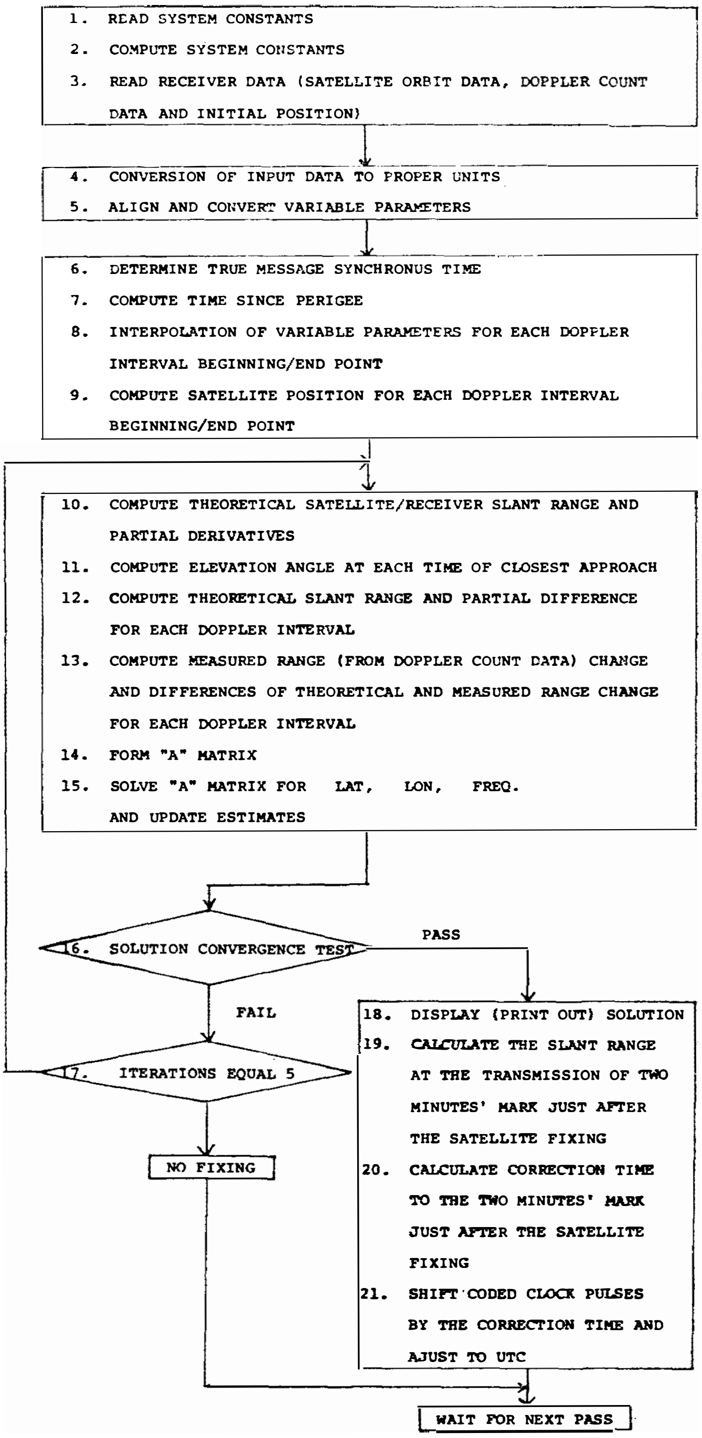

Fig. 5. General flow of the recovery of UTC.

summarizes the recovery of UTC. Items 1–17 describe the usual positioning procedures by an NNSS receiver. Satellite fixing (item 18 in Fig. 5) is considered to occur near the horizon when the receiver is located on the snow field in Antarctica. Then, the slant range at the fixing can approximately be given by $l_0 = \sqrt{2hR+h^2} \cong 3700$ km, as seen from Fig. 3a. The pass correction of the above slant range amounts to about 12.4 ms. The value is not negligible and the items 19–21 in Fig. 5 are required before generating recovered UTC. It is noted that the possible errors in the positioning of 1 mile for latitudinal and/or longitudinal direction and even 2000 m error in height do not affect the accuracy of the recovered UTC since the above values are insignificant in comparison with the pass length.

Since the interrupt rate of the microprocessor in JLE 3300 is 100 Hz, the recovered UTC may have the probable maximum offset of 10 ms. This offset value may seem rather large in comparison with the recovery capability of the relative accuracy within 10–20 μs and the absolute accuracy of ± 200 – ± 300 μs (CASHION *et al.*, 1979). However, the speed-up of the cycle rate would require rather troublesome alteration of both the hardware and the software systems. The offset of 10 ms against UTC can be regarded as in the range of acceptance for the observations of seismic explosion and/or natural seismology. The utility of the altered NNSS receiver was tested by receiving many passes of the five satellites at Tokyo and SYO.

Figure 6 illustrates the examples of simultaneous visigraph outputs of the minute mark of JJY at 8 MHz and that of the recovered UTC. The upper part shows that the satellite fixing of 30130 occurred at 0936LT, June 20, 1981 at Tokyo (35°45′14.4″N, 139°42′42.0″E) which had the closest approach of 73.8

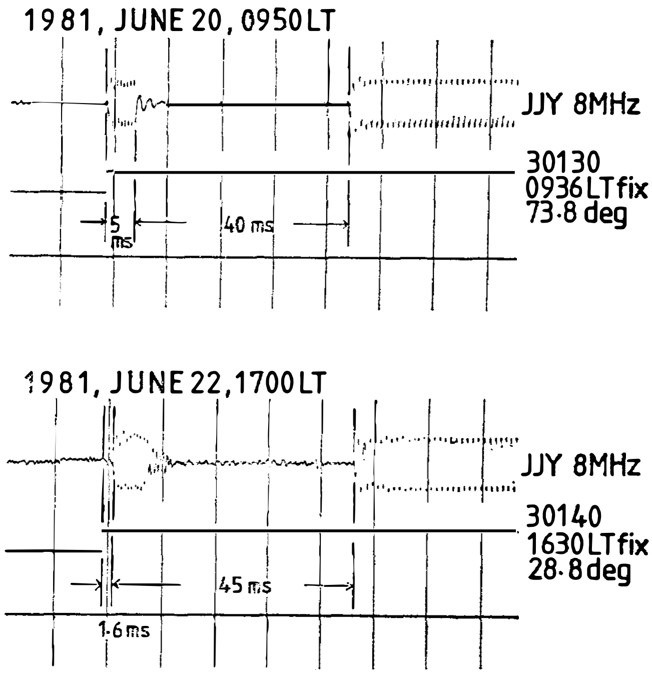

Fig. 6. Simultaneous visigraph output of JJY at 8 MHz and the recovered UTC, which was performed at Tokyo.

degrees elevation angle and that the visigraph output was made at 0950LT after 14 min from the satellite fixing. It shows that the difference of the two minute marks is not more than 1 ms. The lower part shows a similar comparison against another satellite identifier 30140 which was fixed at 1630LT, June 22, 1981. The visigraph outputs at 1700LT after 30 min from the satellite fixing gave 1.6 ms discrepancy between the two time bases. Several experiments at Tokyo in 1979 (before shipped to Antarctica) and in 1981 (after taken from Antarctica) revealed 0–5 ms differences between the minute mark of JJY at 8 or 10 MHz and that of the recovered UTC.

Since the delay time of standard frequency waves JJY 10 MHz at SYO amounts to 50 ms with weak receiving strength and there is no exact way of the path correction, the receiving experiments of the altered NNSS receiver in the antarctic region were made by comparing the recovered UTC with a local time code oscillator which has the frequency stabilities listed in Table 1. Figure 7 illustrates the trend of the local oscillator which was obtained by plotting averaged δt, IRIG-B formatted time code from the local oscillator minus the recovered UTC, in each sampled period I–VI during 240 days' performance test. Each period consists of 2–6 days and the obtained set of δt from sampled 20–100 satellite passes in each period was averaged to give the solid circle in Fig. 7, where the averaged δt in period I was arbitrarily set to zero. The value of 1.2 ± 0.05 ms/day is consistent with the frequency stabilities of the local oscillator (Table 1) and suggests that the recovered UTC does not have significant and unstable offset through 240 days' performance test. Subtracting the trend in Fig. 7, each δt in period I was plotted in Fig. 8 according to the satellite identifier. There are no significant differences among the results against different satellite identifiers. The plotted values for the whole passes in period I show random scatters within ±5 ms.

Table 1. Characteristics of the local oscillator in the IRIG-B formatted time code generator used in the performance test of the altered NNSS receiver.

$\Delta f/f$	$\pm5 \times10^{-10}$/s
	$\pm0.1\times10^{-8}$ /day
	$\pm1.5\times10^{-8}$ /month
	$\pm2 \times10^{-8}$ /year
Temperature characteristic	$\pm1 \times10^{-8}$ (-10 – $+50$°C)

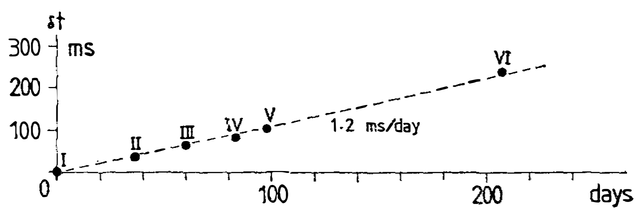

Fig. 7. The obtained trend of the local oscillator after 240 days' performance test.

4. Discussions

The scatters in Fig. 8 reflect the instability of the local oscillator in the altered NNSS receiver. The recovered UTC is not always synchronized with UTC but it will shift resulting from the above instability after the satellite fixing. The performance tests were made by uncontrolling the output time to the visigraph

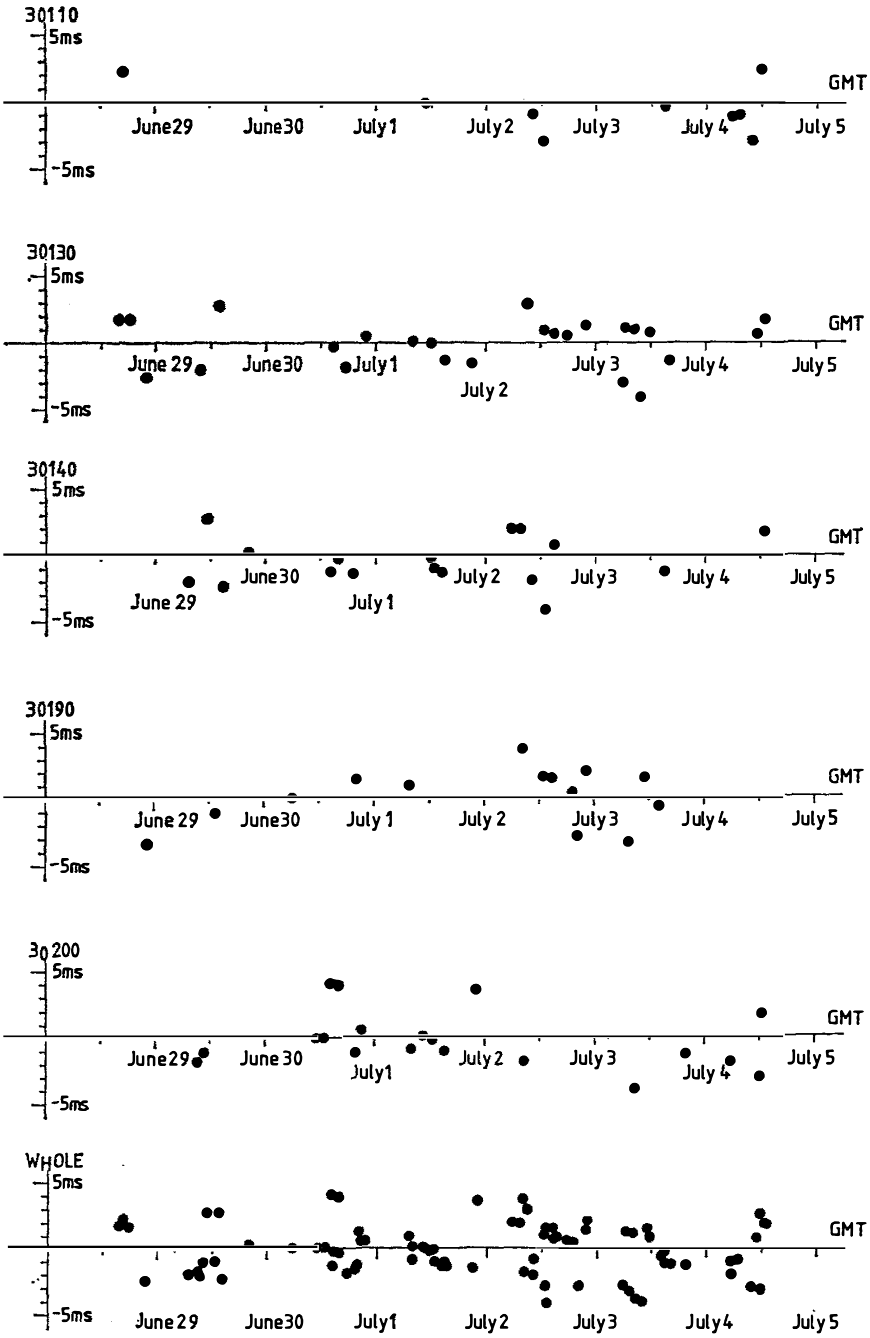

Fig. 8. Plots of δt in period I against each and the whole satellite identifiers, see the text.

after each satellite fixing, which resulted in the time range of 5–120 min. The maximum probable shift in the waiting time (usually less than 60 min in the antarctic region as shown in Table 1 of SHIBUYA *et al.*, 1982) of the next satellite fixing is considered to be 4 ms. The scatters in Fig. 8 also reflect the occasional end time of item 21 in the program flow (Fig. 5). Since the generation of the recovered UTC is controlled by the interrupt cycle of 10 ms, the rounding error in the discrete 10-ms frame may be accompanied. The rounding error is considered to be random in the range of ± 5 ms against the true UTC when many satellite passes are examined. The obtained random scatters in the range of ± 5 ms in Fig. 8 suggest that the above two errors did not sum up so often during the performance tests.

5. Conclusions

The altered 400 MHz NNSS receiver was ascertained to generate the slow rate BCD pulses synchronizing with UTC at a certain two-minutes mark which was broadcasted from an NNSS satellite. The recovered UTC may have the errors which are caused by both the round-off in the 10-ms frame of the interrupt cycle of the processor in the receiver and the instability of the local oscillator during the waiting of the next satellite fixing. The sum of the above errors is considered mostly to be within the range of ± 5 ms against the true UTC. In the three explosion seismic experiments by JARE-21, more than 5 passes were received on a snow field within one or two days both before and after each shot. The offsets of the master clock to the recovered UTC against each shot were determined within the accuracy of 2 ms, consequently shot times of seismic explosions were determined within an overall accuracy of 5 ms. Calibration of the local clock in each DAR recorder to the recovered UTC was also made within the overall accuracy of 0.01 s by the aid of this altered NNSS receiver. It is noted that the offset of the recovered UTC to the true UTC does not accumulate nor is transferred across another satellite fixing. Since the recovered UTC can be obtained without the user's skill so long as the satellite fixing is obtained, it is useful in the field observations for seismology at sea, desert or snow field, though some measures have to be taken to meet the low-temperature circumstances.

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