Adaptive Loop Aiding for Performance Improvement in Weak Signal Environments

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BIOGRAPHY

Faisal Ahmed Khan is currently a Ph.D. student at University of New South Wales. His main area of research is interference effects and analysis in positioning environment. He holds a M. Phil Degree from University of New South Wales, Australia and B.E. (Electronics) degree from NED UET, Pakistan. He has also gained hands-on experience in the field of Satellite Communications at Institute of Space Technology (IST), Pakistan and Pakistan Space and Upper Atmosphere Research Commission.

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Chris Rizos is currently Professor and Head of the School of Surveying and Spatial Information Systems, UNSW. Chris has been researching the technology and high precision applications of GPS since 1985, and has published over 400 journal and conference papers. He is a Fellow of the Australian Institute of Navigation and a Fellow of the International Association of Geodesy (IAG). He is currently the Vice President of the IAG and a member of the Executive of the International GNSS Service.

ABSTRACT

Use of loop aiding for facilitating the operation of GPS receivers in weak SNIR environments has been widely researched in recent years. Locata, a terrestrial radio navigation system working on similar principles as GPS, can also make use of loop aiding techniques with some additional advantages. Locata employs dual-frequency and dual-antenna transceivers (LocataLites) allowing a Locata rover receiver to track four signals from each LocataLite. This paper proposes that the carrier tracking loops (CTL) tracking these signals adaptively aid each other to maintain lock in weak signal and moderate dynamics environment. Performance of this proposed scheme is evaluated and an analytical description and test results of the proposed scheme are presented. Results show that the proposed scheme allows tracking with a loop bandwidth (LBW) of 0.5Hz, operating at 20dB-Hz. A relationship between the aided loop's total phase jitter and the quality of the signal tracked by the aiding loop is also identified and analysed. Using an analytical approach, it is also shown that a lower bound on the aided loop's expected performance is predictable. It is also established that, by using inter-loop aiding, the Locata system gains more than similarly aided GPS receivers.

1. INTRODUCTION:

Operation of GNSS in classically difficult positioning environments has been an issue, particularly with regard to weak received signal levels, poor geometry conditions, and continuously changing multipath scenarios. Locata Corporation's Locata Positioning Network aims to address performance degradation in such situations. A Locata Network (LocataNet) is comprised of time-synchronised terrestrial transceivers (called LocataLites), operating in the 2.4GHz ISM band, transmitting signals appropriate for positioning. Use of time-synchronised transmitters allows single point positioning with centimetre level accuracy. Operation in the ISM band permits signal transmission at much higher power levels than those received from GPS, and avoids any licence requirement. This makes the system feasible for deployment in many situations and environments. However, operation in the licence-free ISM band is vulnerable to RF interference (RFI) from various other devices using the same spectral band. Therefore use of Locata requires that special attention be paid to interference rejection/ mitigation if it is to operate optimally. There have been some improvements in Locata's interference rejection capabilities in the latest released version. However, it has been identified in the authors' previous work [1] that received RFI can cause Locata to operate at sub-optimal levels. In [1], it was identified that some inherent characteristics of the Locata network can be exploited to gain further improvements in terms of noise and interference mitigation. In this paper the authors propose a carrier loop aiding scheme which enables Locata to track signals with carrier-to-noise-and-interference ratio ($C/(N_o+I)$) reduced by noise, interference and/or jamming.

The concept of Doppler aiding using either external aids (e.g. from Inertial Navigation Systems (INS)) or internal aids (from another tracking loop) is not new. Advantages of both types of aiding have been analysed and explored in practice [2], [3]. Such concepts can be applied to any other navigation system, and Locata is no exception. However, the Locata system architecture allows added advantages to be gained from this concept. This is because Locata uses dual-antenna transceivers (LocataLites) with each antenna transmitting signals at two different frequencies. In GPS, currently a maximum of two signals (L1 and L2) are available from all satellites, with L2 tracking only available in high-end RTK receivers. Usually, L1 has been used to aid L2 as the L1 carrier loop provided more accurate estimates of the received signal dynamics [4]. If this aiding signal is corrupted due to received interference at the L1 frequency, the advantages of aiding are lost. With the introduction of the new L2C signal, the data-less channel of L2 becomes a better choice to be used as an aiding signal in terms of sensitivity and reliability (as offered by an increased linearity region and lower frequency) [5]. However, the situation would remain unchanged if the interference is received at the L2 frequency. In Locata, the availability of two carriers being tracked at both frequencies (termed here S1 and S6), offers a solution to this problem. It is likely that both frequency carriers will be differently affected by the received interference. A possible situation could be when a nearby WiFi network uses a channel which is in a co-frequency situation with the Locata S1 carrier. Availability of dual-frequency carriers allows keeping one carrier from each of the two frequencies as an aiding carrier and the other as the aided carrier. In the case where interference is received at either of the frequencies, the other frequency aiding carrier can still provide signal dynamics estimates to both aided carrier loops. This is the kernel of the loop-aiding scheme proposed in this paper. This paper analyses this scheme using simulations and suggests a relationship between the aided loop's total phase jitter and the quality of the signal tracked by the aiding loop.

The paper is organised as follows. After introducing the concept in section 1, section 2 discusses the basics of loop aiding and identifies the problem caused in its absence. Section 3 proposes the solution to this problem and presents the details of the proposed scheme. Section 4 identifies that a lower bound is predictable on the expected performance of the aided loop. Section 5 discusses the simulations performed to test the tracking loop's performance before and after implementation of this scheme and analyses their results. Section 6 finally concludes the paper.

2. LOOP AIDING:

Figure 1 shows a generic un-aided carrier tracking loop. A carrier tracking loop in a radio navigation system receiver has been identified as the weakest link [6]. Its performance is evaluated by analysing its total phase jitter σ_φ, which is given as [2]:

$$\sigma_\varphi = \sqrt{\sigma_{\varphi_o}^2 + \sigma_{\delta\varphi}^2} \qquad \textbf{(1)}$$

where, σ_{φ_o} is the estimated output phase jitter due to wide band noise and interference and is given by:

$$\sigma_{\varphi_o} = \frac{360}{2\pi}\sqrt{\frac{B_L}{C/(N_o+I)}\left(1+\frac{1}{2T\,C/(N_o+I)}\right)} \qquad \textbf{(2)}$$

where B_L denotes the one sided loop noise bandwidth, T denotes the pre-detection integration

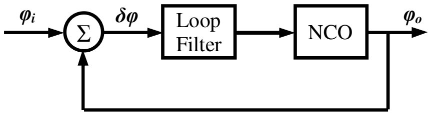

Fig. 1 – Generic Un-aided Carrier Tracking Loop

time and $C/(N_o+I)$ denotes the carrier to noise and interference ratio. Also, $\sigma_{\delta\varphi}$ in **(1)** indicates the phase jitter at the discriminator output and is given by:

$$\sigma_{\delta\varphi} = \sigma_{\delta\varphi_c} + \frac{\sigma_{\delta\varphi_p}}{3} \qquad \textbf{(3)}$$

Here $\sigma_{\delta\varphi_p}$ denotes the dynamic stress error, which for a 3rd order loop is given by:

$$\sigma_{\delta\varphi_p} = \frac{2\pi(5.67)\,j_{\max}}{\lambda B_L^3} \qquad \textbf{(4)}$$

$j_{\max}$ here denotes the maximum value of jerk experienced by the receiver. $\sigma_{\delta\varphi_c}$ in **(3)** denotes the correlated phase errors and is expressed as:

$$\sigma_{\delta\varphi_c} = \sqrt{\sigma_{\delta\varphi_{Tx}} + \sigma_{\delta\varphi_{Rx}} + \sigma_{\delta\varphi_v}} \qquad \textbf{(5)}$$

Here $\sigma_{\delta\varphi_{Tx}}$, $\sigma_{\delta\varphi_{Rx}}$ and $\sigma_{\delta\varphi_v}$ denote the errors due to transmitter clock, local oscillator and platform vibration respectively. Trends of these individual sources of error against different values of bandwidth are depicted in Figure 2. It can be seen that dynamic stress dominates for low bandwidths and noise dominates for high bandwidths. A low cost TCXO is used by both the Locata transmitter and receiver. Here data for plotting vibration and oscillator (TCXO) induced errors is extracted from [2]. Plots assume a value of 30dB-Hz and 0.25g for wide band noise and interference errors and dynamic stress errors. Carrier frequency and wavelength are assumed to be that of the Locata S1 carrier.

For an acceptable operation of a CTL, a theoretical upper limit of total phase jitter has been defined to be 15° [6]. This means that in order to avoid loss of lock, the loop's total phase jitter needs to be minimised. It can be observed from Figure 4 that

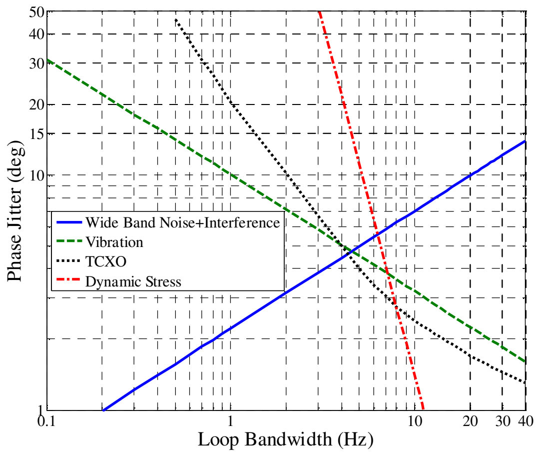

Fig.2 – Individual Sources of Error Contributing to Total Phase Jitter

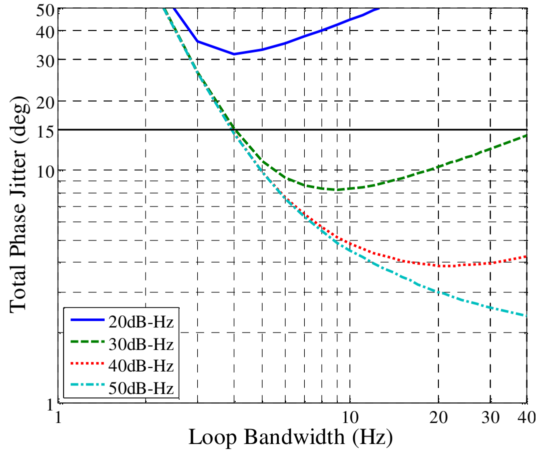

Fig.3 – Theoretical Total Phase Jitter against Loop Bandwidth for Different $C/(N_o+I)$ (Without Loop Aiding).

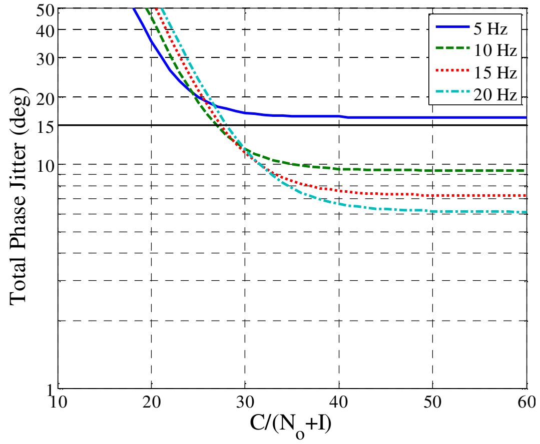

Fig.4 – Theoretical Total Phase Jitter against $C/(N_o+I)$ for Different Loop Bandwidths (Without Loop Aiding).

operation at low $C/(N_o+I)$ values, reduced by noise, interference and/or jamming, is possible if the estimated output phase jitter at these values can be reduced. This can be achieved by operating the loop at lower loop bandwidths. However, jitter introduced by platform dynamics, receiver clock errors and mechanical vibration sets a lower limit on the extent to which this bandwidth can be decreased. In un-aided loops this lower limit varies from 10 – 18Hz depending on the application. If errors contributing to the total phase jitter can be estimated using external information, this can be reduced [2] making the tracking loop more stable in low $C/(N_o+I)$ situations. It has been reported that for GPS, if this aid is obtained from external means (e.g. an INS), errors due to platform dynamics can be estimated and the loop bandwidth (LBW) can be reduced to 2Hz before the loop starts becoming unstable. However, if the aiding is obtained from another tracking loop, operating in the same receiver and tracking signals from the same transmitter, it can help to estimate errors due to receiver clock and vibrations, in addition to dynamics-induced errors [7]. This motivates the proposal of a carrier loop aiding scheme for Locata that can facilitate operations at lower $C/(N_o+I)$ values without the use of external aids.

3. PROPOSED SCHEME

In a Locata receiver, four carrier loops track two signals at each of the two frequencies. Figure 5 shows the carrier chart where A1 and A2 denote the two antennas and S1 and S6 are the two carrier frequencies. It is proposed that two of these four loops be operated with a wider bandwidth of 15-25Hz and the other two loops with a narrower bandwidth. Both of the narrow band loops (NBL) will receive aiding from either of the wide band loops (WBL), depending upon their performance. A loop's total phase jitter has been selected as the performance parameter here. As both the WBL will be tracking the same platform's dynamics and their carrier frequency ratio is close to unity, their total phase jitter will differ mainly due to their $C/(N_o+I)$. If interference is received at one of the frequencies, as discussed before, affecting the total phase jitter of the WBL at that frequency, both NBL will switch to the other, interference-free, WBL for aiding. In this way, both NBL will receive interference-free aiding, unless incoming interference corrupts signals at both the frequencies. In this situation, both NBL will still obtain aiding from the less affected WBL, making their estimates relatively less noisy. Following this scheme, either of the WBL will be adaptively selected to aid both NBL, where WBL will handle dynamics and errors due to other sources and NBL will reject interference.

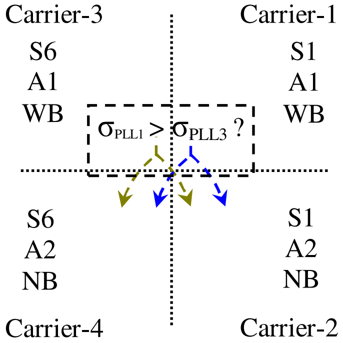

Figure 5 – Locata Carrier Chart

It can be observed from Figure 2 that at higher values of LBW, thermal noise and interference errors dominate. This scheme allows operation at lower LBW, where errors due to this noise and interference do not remain significant. This is achieved by removing the burden of tracking signal dynamics from the aided loops.

In a mathematical sense, consider the signal reaching the tracking loop given by:

$$y(t) = A\sin(2\pi(f_{rel}+f_{osc}+f_{vib}+f_{oth})t+\varphi) \qquad \mathbf{(6)}$$

where
A = received signal amplitude
f_{rel} = relative velocity due to platform dynamics
f_{osc} = oscillator induced frequency errors
f_{vib} = vibration induced frequency errors
f_{oth} = frequency errors due to troposphere, noise and interference and other unmodelled errors
φ = carrier phase at phase detector

Also the aiding signal generated by the WBL is given as:

$$y'(t) = \sin(2\pi(f'_{rel}+f'_{osc}+f'_{vib}+f'_{oth})t+\theta) \qquad \mathbf{(7)}$$

where f'_{rel}, f'_{osc}, f'_{vib} and f'_{oth} denote the error quantities estimated by the aiding WBL. Two quantities f_{est} and f''_{oth} can be introduced here which denote the estimation errors (difference between actual frequency errors at NBL and their estimates generated by WBL) and noise, interference and other unmodelled error differences.

Now, the signal at the multiplier output can be represented as:

$$yy'(t) = \sin(2\pi(f_{est} + f''_{oth})t + \psi)$$

(8)

The frequency sum term generated by the multiplier will be removed by the subsequent filtering and is therefore not mentioned further. The in-phase and out-of-phase components can be written as:

$$yy'_I(t) = \sin(2\pi(f_{est} + f''_{oth})t + \psi)$$
$$yy'_Q(t) = \sin(2\pi(f_{est} + f''_{oth})t + \psi + 90^o)$$

(9)

Now the NBL has to effectively track errors $f_{est} + f''_{oth}$ which are (relatively) less than the actual errors. As a result a very low bandwidth can be used to track these errors.

4. PREDICTION OF LOWER BOUND:

It must be emphasised that in this scheme aiding is obtained from another loop, instead of some external device such as an INS. For this reason, although the errors due to platform dynamics, vibration and local oscillator (receiver clock) are reduced, additional phase errors due to noise and interference are induced from the aiding loop. This introduces a composite thermal noise error in the final signal generated by the aided loop's NCO. This composite error can be expressed as:

$$\sigma^2_{\varphi_o,comp} = \sigma^2_{\varphi_o(aiding)} + \sigma^2_{\varphi_o(aided)} + 2\sigma^2_{\varphi_o(aiding,aided)}$$

(10)

where $\sigma^2_{\varphi_o(aiding,aided)}$ denotes the aiding and aided loops' noise and interference error co-variance. The total phase jitter of the aided loop will consist of these composite errors in addition to estimation and other unmodelled errors. Therefore **(11)** suggests a lower bound on the total phase jitter of the aided loops, as these will be present even if the signal dynamics estimates are very close to the actual values.

Also, **(12)** suggests a relationship between the aided loop's total phase jitter and the quality of the signal tracked by the aiding loop. A better performance of aided loop would require a relatively interference-free and less-noisy estimate from the aiding loop. Where the aiding loop's measurements are corrupted by received interference, the aided loop's performance will be degraded instead of being improved. A loss of lock can also occur for the aided loop in this situation depending upon the quality of the aiding information.

5. SCHEME IMPLEMENTATION

In order to analyse the proposed scheme, Locata signals were simulated according to the available specifications [8], and were processed using a software receiver. Different scenarios were simulated where interference on either or both of the frequencies was considered. The same vehicle dynamics profile, as shown in Figure 6, was considered for all tests.

A. UN-AIDED LOOP PERFORMANCE

First we consider the situation for un-aided loops in order to determine loop tracking performance without implementation of the proposed scheme. Figures 7 and 8 show the phase jitter in the absence of any aiding plotted against loop bandwidth (LBW) and $C/(N_o+I)$. It can be readily noticed here

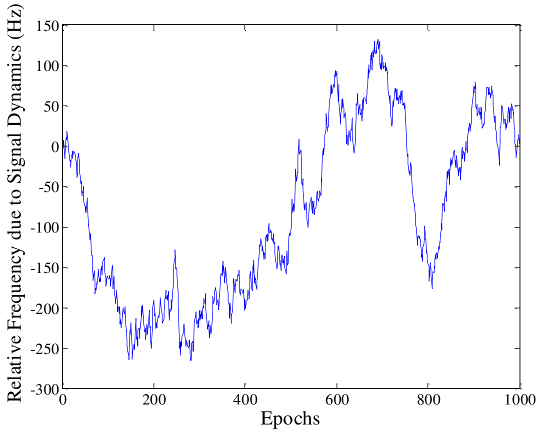

Fig. 6 – Relative Frequency Variation due to Signal Dynamics

that the phase jitter is significantly dependent on LBW for all values of $C/(N_o+I)$. At lower values of LBW the phase jitter curves for different values of $C/(N_o+I)$ start to converge. This convergence point is jointly determined by the signal dynamics (due to platform dynamics, clock and vibration induced noise) and $C/(N_o+I)$. Signal dynamics and the thermal noise and received interference set the upper and lower bounds on the LBW. This results in a trade-off for an optimal value of LBW to minimise this phase jitter. This can be understood by noting the error trends in Figure 2. The errors due to signal dynamics tend to increase at lower LBW, while at higher LBW wide band noise+interference induced errors become dominant. These two factors jointly set a minimum achievable phase jitter value. The heavy line in both graphs at 15^o phase jitter indicates the theoretical upper limit on phase jitter as defined in [6]. From Figure 8 it can be observed that for LBW of 8Hz the loop operated very close to this limit. It was found that the carrier loop was not able to maintain lock at LBW 7Hz and less for the vehicle dynamics defined by Figure 6.

B. AIDED LOOPS' PERFORMANCE

From the above discussion, it can be seen that in order to reduce the phase jitter the effect of at least one of the abovementioned factors needs to be reduced. A possible way of achieving this, as discussed above, is by obtaining external or internal estimates of signal dynamics. External Doppler estimates can be obtained using an INS in an ultra-tight configuration [9]. However this introduces synchronisation issues and other implementation problems. In our proposed scheme the signal dynamics estimates are obtained from another carrier loop with a wider bandwidth operating at the same or different frequency. This aiding from either a co-frequency or cross-

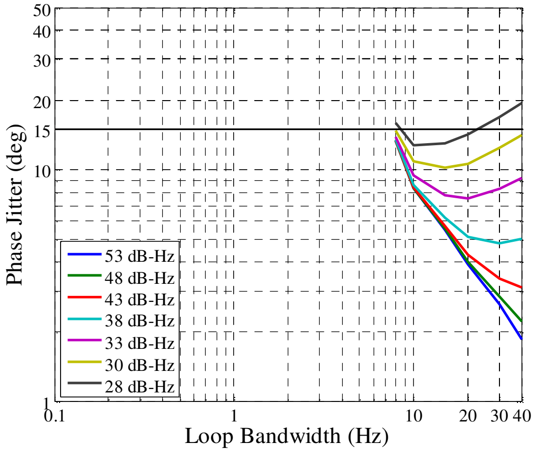

Fig.7 – Phase Jitter against Loop Bandwidth for Different $C/(N_o+I)$ (Without Loop Aiding).

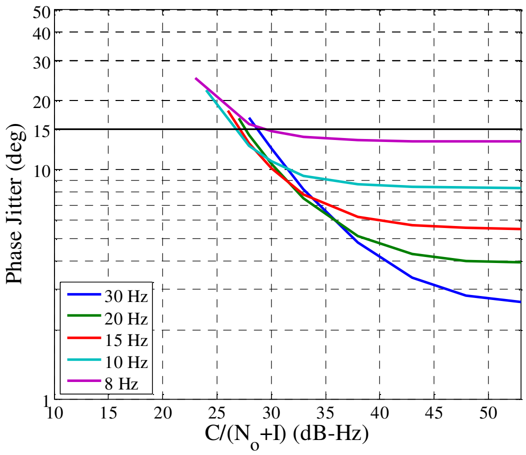

Fig.8 – Phase Jitter against $C/(N_o+I)$ for Different Loop Bandwidths (Without Loop Aiding).

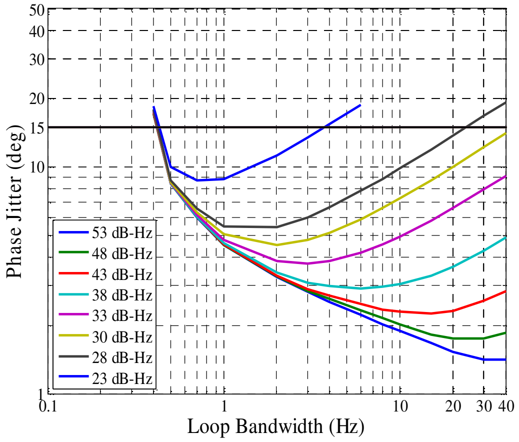

Fig.9 – Phase Jitter against Aided Loop's Bandwidth for Different Aided Loop's $C/(N_o+I)$ (With Loop Aiding).

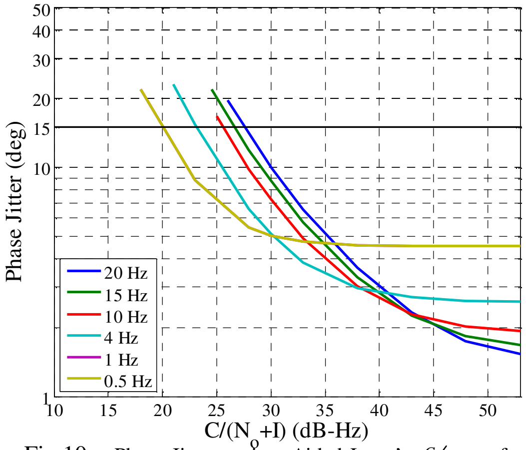

Fig.10 – Phase Jitter against Aided Loop's $C/(N_o+I)$ for Different Aided Loop's Bandwidth (With Loop Aiding).

frequency loop removes the burden of signal dynamics estimation from the aided loop, thus allowing it to operate at lower LBW. Operation at lower bandwidths facilitates noise rejection making it possible to track signals with reduced $C/(N_o+I)$ values.

Figures 9 and 10 depict the situation after implementation of the proposed scheme. Here the aiding WBL were operated with a LBW of 25Hz. Wide band noise+interference was alternatively introduced in one of the WBL, while the other WBL operated at a fixed $C/(N_o+I)$ of 53dB-Hz. Both the NBL observed the jitter estimates from both the WBL and used the less noisy ones, after appropriate scaling according to frequency differences.

In order to observe the adaptive switching of an NBL for signal dynamics estimates, implementation results are shown in terms of discriminator outputs. Figure 11 shows the discriminator outputs for both WBL and NBL at both S1 and S6 frequencies. These results show the situation when aiding and the aided loops had 25Hz and 1Hz loop bandwidths. For the noisy situation, $C/(N_o+I)$ was maintained at 30dB-Hz. Wide band noise+interference alternatively affecting both WBL can be noticed in Figure 11. For the NBL, it can be seen that the noise was suppressed by the narrower loop bandwidths for the whole period of the test.

It was observed that the NBL at the interfered frequency was able to maintain lock down to a bandwidth of 0.4Hz. After this, the loop was not able to maintain lock at any of the tested $C/(N_o+I)$ values. This threshold of 0.4Hz for loss of lock was the same for all tested $C/(N_o+I)$ values because all curves converged at this point and would have produced the same phase jitter if they were able to maintain lock below this bandwidth. This point can be confirmed by inspecting the curves of 28dB-Hz and higher. All these curves converge at 0.5Hz and from there on produced the same amount of jitter.

Looking at the situation from another direction, Figure 10 shows the phase jitter values plotted against $C/(N_o+I)$ for the aided loop operating at different bandwidths. As expected, a higher aided loop bandwidth maintained a lower value of jitter at higher $C/(N_o+I)$. However, at lower values of $C/(N_o+I)$ the loop with these higher bandwidths lost lock before the one with a lesser bandwidth. This

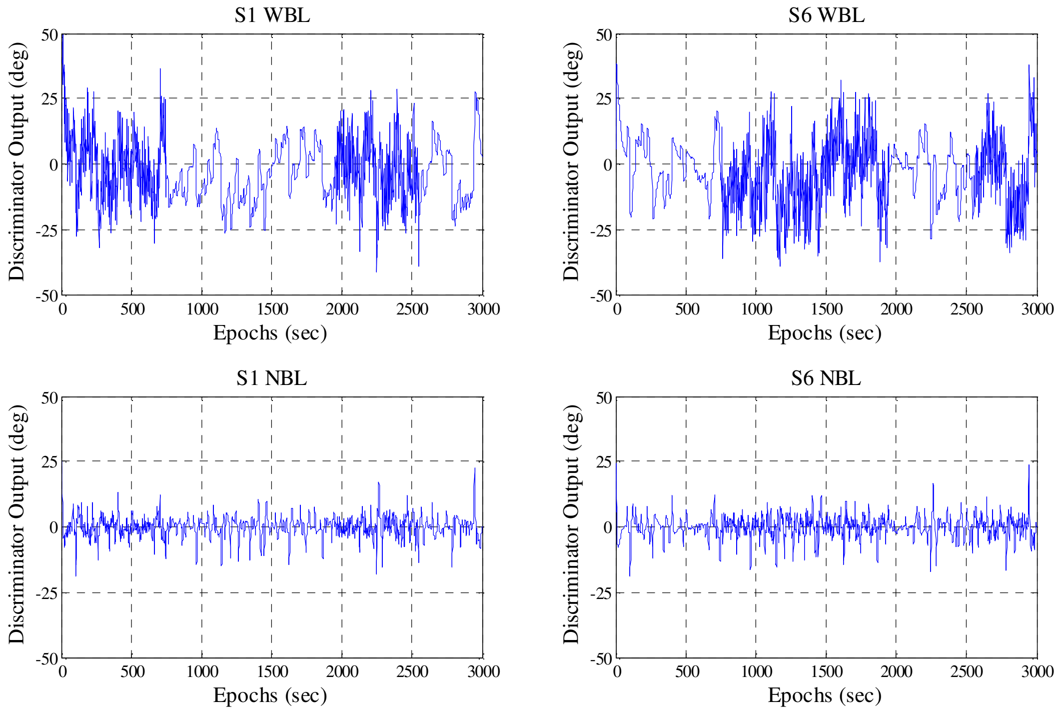

Fig.11 – Raw CTL Discriminator output for Wide and Narrow Band Loops.

was due to the fact that at higher bandwidths jitter due to noise and interference dominates, which keeps the loop from maintaining lock at low $C/(N_o+I)$ values.

In an un-aided situation, a loop fails to remain in lock at narrower LBW due to increased phase jitter induced by signal dynamics. Aiding here lessens its influence by providing a signal dynamics estimate. The fact that the effects of signal dynamics are reduced is also confirmed by the movement of the minimum jitter point from a higher LBW to a lower LBW at reduced $C/(N_o+I)$. Figure 8 shows that in an un-aided situation, with a loop bandwidth of 10Hz, the 15° theoretical limit is exceeded when the signal level dropped below 27dB-Hz. However, it can be seen from Figure 10 that this jitter value was not exceeded until the signal level dropped below 20dB-Hz, while operating with a loop bandwidth of 0.5Hz. This shows that a margin of 7dB-Hz was achieved against received wide band noise+interference, while the loop was able to operate with a smaller bandwidth.

In order to further explore the proposed scheme, the aiding loop was operated at different LBW and $C/(N_o+I)$ values. To this point the aiding loop has been assumed to be tracking a signal at 53dB-Hz. In a real-world scenario this may not be the case. It is highly likely that $C/(N_o+I)$ would fluctuate due to various factors, including received interference. It may be the case that the interference is received at both of the frequencies. In this case $C/(N_o+I)$ will be reduced for both of the WBL.

In order to analyse the performance of the proposed scheme in such a situation, interference was assumed to be present at both frequencies. This made the $C/(N_o+I)$ for all the loops degrade from an optimistic value of 53dB-Hz. Performance of aided loops, in this situation, in terms of phase jitter is depicted in Figures 12 and 13. For this test, the aided loop and the aiding loop were operated with 1Hz and 25Hz bandwidths respectively. $C/(N_o+I)$ of the signal tracked by aiding loop was varied in the range 53 – 33dB-Hz, while for the aided loop it was kept fixed at 30dB-Hz. It can be observed from Figure 12 that the aided loop lost lock at a similar bandwidth to the previous aided case. This was due to the fact that as the aiding loop's bandwidth remained fixed at a high value, the quality of signal dynamics estimates was less affected. This kept the aided loop's jitter at similar values at lower bandwidth, while it degraded for higher bandwidths due to the aiding loop's degraded $C/(N_o+I)$. Another interesting point to note here is that in this case, the minimum achievable jitter value increased as the aiding loop signal's $C/(N_o+I)$ decreased. This is in accordance with equation **(13)**. As expected, a relationship between the quality of the signal tracked by aiding loop and the achievable performance by the aided loop can be easily noticed here. Figure 13 illustrates the same fact, where reflection of the aiding loop's signal quality degradation can be noticed in the aided loop's achieved jitter at various $C/(N_o+I)$. It can be inferred that the operation of the aided loop at further

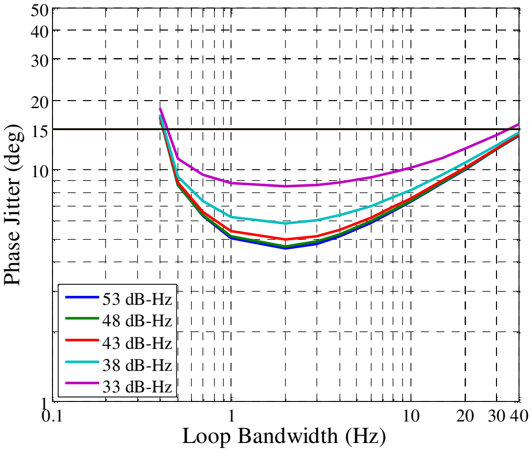

Fig.12 – Phase Jitter against Aided Loop's Bandwidth for Different Aiding Loop's $C/(N_o+I)$ (With Loop Aiding).

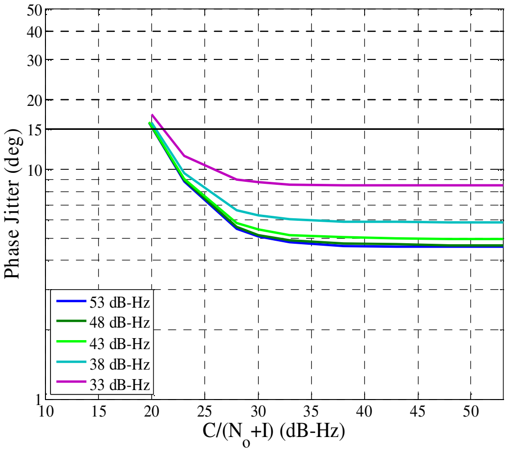

Fig.13 – Phase Jitter against Aided Loop's $C/(N_o+I)$ with Aiding Loop at Different $C/(N_o+I)$ (With Loop Aiding).

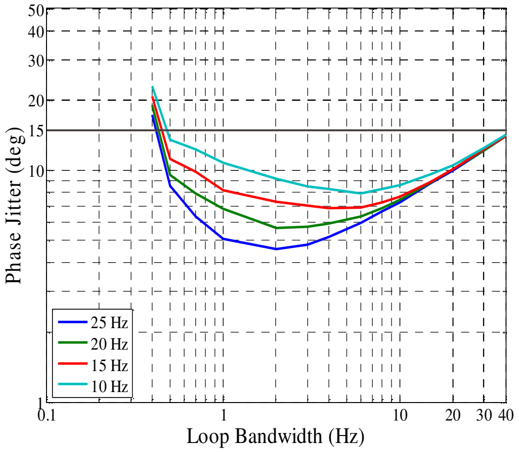

Fig. 14 – Phase Jitter against Aided Loop's Bandwidth with Aiding Loop at Different Loop Bandwidths (With Loop Aiding).

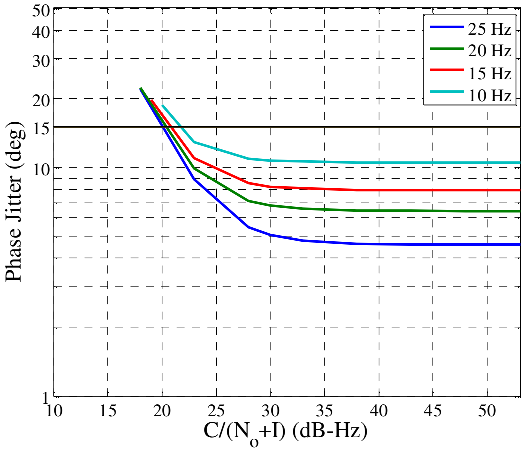

Fig.15 – Phase Jitter against Aided Loop's $C/(N_o+I)$ with Aiding Loop at Different Loop Bandwidths (With Loop Aiding).

reduced bandwidths will be more vulnerable to loss of lock. Also, the observations discussed above suggest that a lower limit on the aiding loops' performance needs to be set in order to gain advantage from the proposed scheme.

To further evaluate the proposed scheme's performance, the aiding loop's bandwidth was varied while keeping the aiding signal's $C/(N_o+I)$ constant. Again the aiding loop was operated at 53dB-Hz, with loop bandwidth varying in the range 10 – 25Hz. Figures 14 and 15 show the aided loop's performance for such a situation. Figure 14 shows the aided loop's phase jitter variation against its bandwidth. It can be noted that the as the aiding loop's bandwidth was reduced, the quality of its signal dynamics estimates degraded. This caused the degradation in aided loop's jitter at lower loop bandwidths. Similarly, as expected, at higher aided loop bandwidth, its jitter quality remained similar for different values of aiding loop bandwidth. This was due to the fact that the aiding loop was able to reject more wide band noise+interference at reduced bandwidths.

6. CONCLUDING REMARKS

An adaptive inter-loop aiding scheme is proposed and analysed in this paper. This scheme employs the concept of loop aiding without requiring any external estimates. It is established that the inter-loop aiding reduces phase jitter, allowing operation at $C/(N_o+I)$ values reduced by wide band noise and interference. It is also shown that a margin of 7dB-Hz can be achieved while operating at 0.5Hz loop bandwidth. However, it should be noted that this margin is optimistic and may degrade in a real-world scenario due to unmodelled errors. It was established that the quality of the aiding signal and the aiding loop's bandwidth will dictate the quality of aiding and eventually the aided loop's performance. Considering this fact, it was shown that a lower bound is predictable on the aided loop's performance. The proposed scheme, by adaptive switching to either of the WBL for aiding, offers performance improvements even if interference is experienced at both frequencies.

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