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Titolo

La generazione e distribuzione dei riferimenti di tempo e frequenza della Stazione Radioastronomica di Medicina.

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Rapporto Tecnico XXX

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Premessa

In occasione dell'attuale ricambio generazionale è importante richiamare in estrema sintesi i principi motivanti la progettazione, costruzione ed operatività del laboratorio Tempo e Frequenza (T&F), nato concomitante alla parabola VLBI di Medicina.

Introduzione

La scelta di entrare a far parte della rete di Osservatori radioastronomici operanti con la tecnica VLBI ha innescato la necessità di dotare anche la stazione Radioastronomica di Medicina BO, fin dal 1983 durante la costruzione stessa della parabola di 32m, di un ***laboratorio*** dedicato alla misura e verifica della stabilità di fase dei nuovi ricevitori, anch'essi progettati e realizzati all'interno dell'Istituto, per soddisfare tutte le nuove specifiche richieste dalla tecnica VLBI. Questa tecnica richiede infatti che venga preservata non solo l'ampiezza ma soprattutto la fase ($\Delta\varphi << 1$rad) dei segnali radioastronomici durante sessioni osservative che possono protrarsi fino a molte ore e/o estendersi fino alle massime frequenze di ricezione della parabola di 32 metri (22GHz al tempo del progetto iniziale, oggi potenzialmente anche molto maggiori, fino a 100GHz). E' immediato allora calcolare l'ordine di grandezza della "fractional frequency stability", richiesta ai ricevitori fino dall'inizio delle operazioni, come prodotto di 2^{10} Hz per 10^4 secondi, ovvero instabilità di fase di poche parti in 10^{-14} ($\Delta\varphi=2\pi f*\Delta t$) o inferiori. In pratica si è reso necessario prevedere la generazione e distribuzione di riferimenti di Frequenza e Tempo ottenibili solo con i più moderni campioni atomici disponibili in quell'epoca storica. La scelta quasi ovvia ricadde sul Maser ad Idrogeno (H-MASER) (Vedi Fig. 1) che veniva venduto come la combinazione (= phase lock loop) del segnale fornito da un ottimo oscillatore a quarzo a 5MHz con quello a 1420MHz, uscente da una cavità risonante al salto quantico nell'orbita fondamentale di elettroni dell'idrogeno, opportunamente eccitati. Si poteva ottenere così un riferimento di fase, ultra-stabile: sia a corto termine (per la generazione delle frequenze più alte) che a lungo termine (necessario per l'integrazione del segnale radioastronomico per tutta la durata di una sessione di osservazione) per i sintetizzatori da utilizzare come Oscillatori Locali (LO) dei nostri ricevitori.
Non occorrono super esperti per capire che, pur avendo a disposizione simili riferimenti di stazione presso ciascuno dei radiotelescopi, distanti fra loro anche migliaia di chilometri, che intendono partecipare ad una osservazione di tipo VLBI, gli H-Maser non possono garantire, da soli, la coerenza di fase necessaria ad ottenere il prodotto interferometrico ottimale fra i segnali radioastronomici raccolti in ogni Osservatorio. Di qui la necessità di saper individuare i circuiti più critici e maturare l'esperienza di progettazione necessaria anche in questo campo.

E' stata nostra cura quindi dotare il laboratorio di quanto necessario per raggiungere questo obiettivo. Vogliamo qui descriverne le caratteristiche fondamentali, per lasciare memoria storica dei criteri da noi utilizzati nella configurazione hardware/software attuale e per permetterne ora, una chiara e facile manutenzione, ed in futuro, risultare utile per i progetti che il nuovo personale dell'Istituto vorrà produrre.

Finalità del laboratorio T&F della Stazione Radioastronomica di Medicina

Ogni catena di ricezione VLBI è costituita da diversi stadi che operano dalla più alta "sky frequency", (quella di ricezione dell'antenna del radiotelescopio) fino alle frequenze più basse della "banda base" per registrarle, un tempo su nastro magnetico o hard disk, ora su server o trasferiti in tempo reale via Internet. Il confronto diretto fra i loro vari contributi nel determinare la stabilità totale richiede di passare dal dominio delle frequenze a quello del tempo, ovvero al mondo dei "picosecondi". Questo fu per tutti noi e non solo, una totale novità: soprattutto perché il VLBI richiede contemporaneamente le stabilità a corto termine della generazione di segnali a microonde, ma anche quella a lungo termine, tipica della metrologia del Tempo. Apparve poi subito chiaro che sarebbe stato necessario creare un laboratorio T&F, tale da poter funzionare per decenni e garantirne, parimenti, flessibilità per gli sviluppi futuri.

Per raggiungere gli obbiettivi sopra citati si fornisce un elenco di caratteristiche, in ordine di priorità.

1) **Affidabilità**: la stabilità sia di frequenza che di tempo è vista come un *servizio* essenziale per tutto l'Osservatorio, ma, proprio per questo, tutti si aspettano che venga fornita come un dato certo, senza necessità di ulteriori interventi (esclusi quelli forniti come manutenzione ordinaria). Una affidabilità ***duratura*** richiede ovviamente a sua volta una *progettazione* iniziale oculata, basata su scelte competenti di componenti di provata qualità; ma anche la *ridondanza,* estesa a quanti più blocchi funzionali possibili, a partire dalle alimentazioni e poi nella generazione e distribuzione dei segnali di riferimento. Il loro dimensionamento deve quindi considerare *priorità di utilizzo*, loro criticità d'uso, distribuzione logistica ed altro ancora. Da non trascurare poi in un impianto esteso come la stazione di Medicina, la sua vulnerabilità ai fulmini che hanno storicamente procurato pochi danni, solo perché furono previsti, a priori, vari isolatori ad hoc e, più recentemente, l'uso generalizzato di fibre ottiche.
2) **Unicità** della generazione *coerente* fra Tempo e Frequenza da distribuire ai vari circuiti e/o utenti utilizzatori. Questo può essere un requisito fondamentale solo se si tratti di VLBI; in altre applicazioni potrebbe esserlo di meno. Resta però conveniente che il centro di produzione di tutti i segnali sia concentrato nello stesso luogo per permettere sia semplici verifiche, come pure controlli incrociati ad alta risoluzione (le scale di Tempo si possono perdere anche solo con un guasto istantaneo. L'accuratezza nella ripartenza dipenderà allora da quale dispositivo si utilizzerà per il riaggancio).
3) **Versatilità.** In pratica abbiamo constatato come la "fame" di sempre nuovi riferimenti, non necessariamente super accurati, siano spesso legati al nascere di nuovi programmi di ricerca con finalità diverse. Di qui la continua necessità di prevedere sempre nuove linee opportunamente disaccoppiate, tramite distributori ad alto isolamento (da non dimenticare che in VLBI anche una sola connessione/distacco da un'altra porta del distributore in uso, può produrre salti di fase inaccettabili!) e comunque vicendevolmente protette (corti circuiti et al.).

4) **“Common clock”**. Il moderno uso di fibre ottiche anche nei collegamenti intraeuropei o intercontinentali, con stabilità su brevi periodi anche superiori a quelle ottenibili con singoli riferimenti atomici locali, non deve in ogni caso concedere *alcun compromesso* sulla affidabilità operativa. Tra l’altro i più moderni programmi di ricerca prevedono risoluzioni temporali sempre maggiori, incompatibili con interruzioni di servizio anche minime.
5) **Frequenza e/o Tempo?** Sin dall’inizio c’è stata una certa incomprensione su questa differenza, soprattutto verso la scala di tempo da usare in VLBI: UTC od altri standar. Non bisogna mai dimenticare che in Interferometria, il confronto è in *frequenza*, fra i segnali registrati nei diversi Osservatori della rete (fringe search). La sincronia temporale iniziale fra gli ***orologi*** di due Osservatori VLBI si può infatti ottenere dai dati stessi al momento della correlazione, calcolando il ritardo per cui si ha il massimo della frangia interferometrica. Onde evitare inutili sprechi di tempo, attualmente, ogni stazione T&F di ogni Osservatorio VLBI fornisce la storia di questo valore (CLOCK OFFSET) come risulta, nel nostro caso, da misure orarie H24 ottenute da ricevitori GPS, omologati per *timing di precisione*. La registrazione e successiva archiviazione dei valori di clock offset rappresenta quindi uno dei task prioritari nella gestione quotidiana della stazione T&F. È opportuno qui anche ricordare che questa stima iniziale NON va confusa con il ritardo di fase relativa fra i vari Osservatori determinato per uso Geodinamico od altre analisi offline.

Fig.1

H-MASER (I74) Lo H-MASER installato a Medicina è siglato I74. A sinistra lo H-Maser è contornato da un tavolino che a sua volta supporta il Comb Generator di INRIM per l’aggancio con fibra ottica ai campioni ottici di INRIM (vedi testo).

Il laboratorio di Tempo & Frequenza presso la parabola VLBI “G. Grueff”.

Alla luce di quanto descritto finora, appare evidente come la stazione T&F di ogni Osservatorio VLBI agisce come il suo “cuore pulsante”, in quanto sincronizza ogni azione facente parte di una sessione di acquisizione dati di tipo VLBI. A seconda della frequenza operativa di ogni singolo blocco funzionale della catena di ricezione, risulteranno diversi i singoli requisiti di stabilità necessari per ciascuno di essi (non ultimi quelli dovuti a gradienti termici dell’ambiente in cui essi operano). Le osservazioni radioastronomiche alle frequenze di cielo più alte impongono i limiti più restrittivi, come è già stato mostrato ($\varphi=2\pi f$) ed essere stato individuato come “*stabilità a corto termine*”.

In particolare, la ricezione fino nelle microonde richiede la generazione di segnali di oscillatore locale (OL), tramite catene di sintesi di frequenza (phase lock loop) e/o semplici moltiplicatori, caratterizzati da una pulizia spettrale molto elevata, (si ricorda che il segnale risultante dopo ogni conversione di frequenza del ricevitore, ricopia le stesse instabilità dei segnali di OL). Si deve tener conto infatti che in ogni moltiplicazione di frequenza per generare i LO necessari per far osservazioni in banda K (ed a breve anche a frequenze ben più alte) sorge il problema che le instabilità di fase degradano *non meno* di un fattore pari a 6dB per ogni moltiplicazione per 2 della frequenza. La Fig. 2 mostra, come esempio, il tipico tracciato del Phase Noise, espresso come $S\varphi$ (densità spettrale delle fluttuazioni di fase, espressa in dBc, ovvero rispetto alla potenza contenuta nella portante SSB, in 1Hz di banda). Ecco perché il quarzo del Maser-H fu da noi selezionato, con particolare insistenza presso il costruttore, con le specifiche di Phase Noise migliori in assoluto rispetto a quelle disponibili.

In modo analogo con il termine *stabilità a lungo termine* si vuol intendere la capacità di mantenere nel tempo la stessa relazione di fase del segnale di OL, rispetto ad un segnale teorico perfetto. Nella radioastronomia si utilizza questa proprietà per integrare il segnale radioastronomico il più a lungo possibile, migliorando la sensibilità osservativa, come evidenziato nell’equazione che segue (ma in modo compatibile con tutte le altre cause di instabilità sperimentali). Vedi allegato 7 in cui si tratta fondamenti della tecnica VLBI.

$$SNR = \frac{S}{2k}\frac{\sqrt{A_1 A_2}}{T_s}\sqrt{2B_0T}$$

Dove: S è il power flux density della radiosorgente puntiforme
A_1 e A_2 media geometrica delle aperture delle antenne
B_0 è la larghezza di banda registrata
T è il tempo di Integrazione
T_s è la temperatura di sistema
k è la costante di Boltzmann

In questo caso si deve curare soprattutto la stabilità di temperatura di ogni singolo componente della catena di ricezione VLBI, sia attivo che passivo (cavi di collegamento RF compresi!).

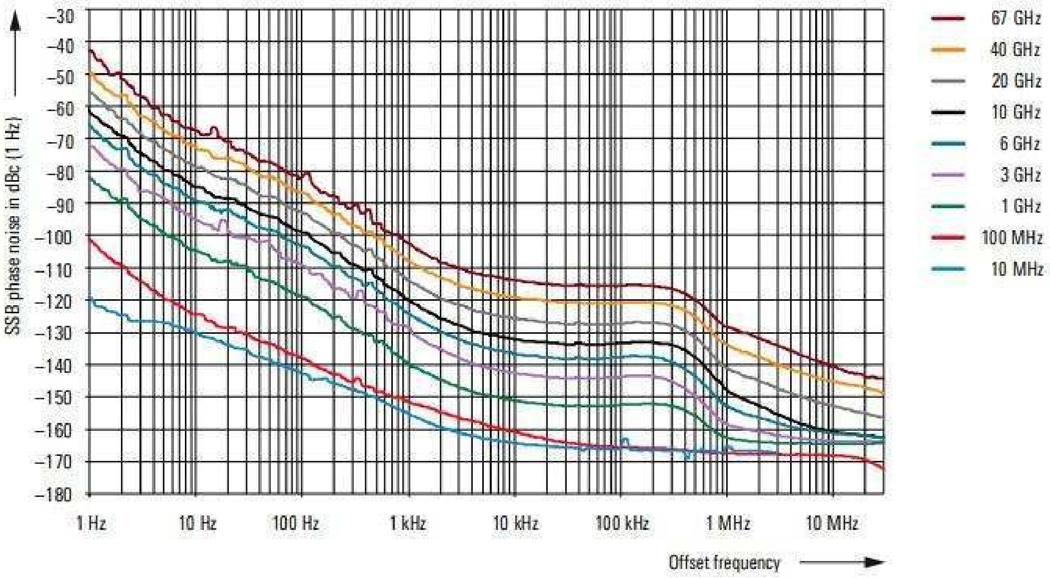
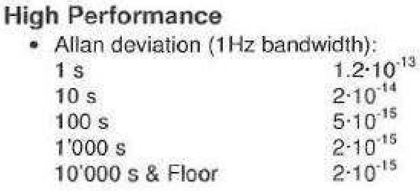


Fig. 2

Caratteristica del Phase Noise dichiarato per i sintetizzatori Rohde & Schwarz, serie SMA-100

Per completezza della documentazione, riportiamo qui le caratteristiche dichiarate dal costruttore per il nostro campione atomico secondario H-MASER:

1. stabilità 1.2 E-13 @ 1s

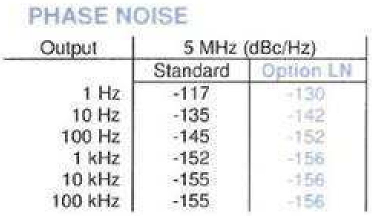


High Performance

- Allan deviation (1Hz bandwidth):

1 s	$1.2 \cdot 10^{-13}$
10 s	$2 \cdot 10^{-14}$
100 s	$5 \cdot 10^{-15}$
1'000 s	$2 \cdot 10^{-15}$
10'000 s & Floor	$2 \cdot 10^{-15}$

2. Purezza spettrale -127 dBc @ 1Hz



PHASE NOISE

Output	5 MHz (dBc/Hz)	
	Standard	Option LN
1 Hz	-117	-130
10 Hz	-135	-142
100 Hz	-145	-152
1 kHz	-152	-156
10 kHz	-155	-156
100 kHz	-155	-156

Alimentazioni ridondanti per operazione UPS

Tutte le apparecchiature sensibili VLBI e quindi anche i circuiti di distribuzione dei segnali di riferimento T&F, sono alimentate a partire dalla 220V da un gruppo UPS alimentato o a batterie o via gruppo elettrogeno. Per tentare di escludere anche *l'impossibile*, abbiamo aggiunto un altro livello di ridondanza, predisponendo due pacchi di due batterie da 24Vdc, che con il loro alimentatore dedicato, hanno la capacità di mantenere correttamente in funzione tutta la stazione T&F per almeno 24 ore, anche in assenza totale di altre fonti di energia elettrica a tensione di rete (240 Vac). Da non dimenticare però la completa sostituzione delle batterie tampone tipicamente ogni 8 anni! (Fig. 3)

Fig. 3

I 2 pacchi batterie da 24Vdc alloggiati all'interno della console e nella stanza H-MASER

La logistica del laboratorio di T&F

Si è già accennato come la collocazione del laboratorio di T&F, raggruppata in un unico luogo, abbia avuto una precisa giustificazione operativa; qui aggiungiamo che si è voluto espressamente separare questa zona in due stanzette contigue, chiuse da porte indipendenti, soprattutto per fornire, ai campioni atomici di frequenza, un isolamento termico ottimale ed, al personale di ricerca, una abitabilità controllata. Potrebbe sembrare un'esagerazione, ma appunto nella pratica quotidiana si è riscontrato come possa capitare facilmente che, in assenza del personale preposto, avvengano poi anche semplici manomissioni che possono poi modificare quantomeno la termica di questi locali.

Un altro requisito del locale Maser fu legato alla sensibilità dei primi campioni atomici alle vibrazioni del terreno. Le loro pompe ioniche (alimentate a 5 KVolts), necessarie a mantenere il vuoto all'interno della cavità risonante nonostante la continua immissione di nuovo Idrogeno atomico, potevano facilmente produrre archi di corto circuito con perdite istantanee di vuoto.
Di qui la soluzione di isolare meccanicamente la base di supporto del Maser con una fondazione indipendente dal fabbricato circostante e riempita di sabbia.
Una spessa lastra di marmo chiude la "vasca" di sabbia e fa da supporto allo H-Maser. (Fig. 4)

Fig. 4

Particolare dell'alloggiamento in camera termostatata con vasca riempita di sabbia sulla quale è posata una lastra di marmo come basamento per il maser.

Per fortuna la nuova serie di H-Maser ora installata a Medicina è molto meno sensibile alle vibrazioni del terreno, perché utilizza come pompe da vuoto sia dei "getter" statici (non alimentati) che modelli di pompe ioniche più affidabili a 3,5KV.
Ciò ha significato una riduzione drastica della manutenzione, potendo evitare la sostituzione biennale di entrambe le vecchie pompe ioniche e quindi maggiore affidabilità e costi più contenuti.
Per finire si vuol citare la cura nel progetto del sistema di condizionamento termico della stanza Maser. In questo caso si sono volute evitare al massimo le *pendolazioni* tipiche degli impianti ON/OFF con un controllo proporzionale pilotato da un dispositivo Honeywell al decimo di grado e sfruttando l'elevata inerzia termica di un considerevole accumulo d'acqua, collocato sotto il basamento dell'antenna. Al momento di questa stesura la temperatura della stanza Maser (Fig. 5) è settata fissa a 22°C (estate ed inverno) nonostante che nel tempo si siano rese necessarie alcune variazioni di settaggio a causa di interventi di ristrutturazione avvenuti alla palazzina parabola.
Si ricorda che, nonostante questi controlli, mantenere la luce accesa o spenta nel locale Maser può produrre variazioni nella marcia del Maser quando analizzata al massimo della risoluzione possibile. Non parliamo quindi di dimenticare aperta la porta di quel locale o di entrare fisicamente di persona!
La schermatura da campi magnetici esterni è concentrata negli strati di Mumetal del contenitore stesso del Maser. L'effetto residuo inevitabile proviene dalla rotazione dell'antenna.

Fig. 5

Alloggiamento del H-MASER in stanza termostatata ed il sistema laser comb INRIM.

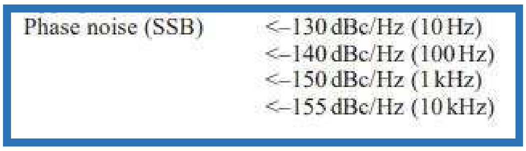
Ridondanza del campione atomico locale

Il laboratorio è dotato di ulteriori due campioni secondari di frequenza, questi usano una sorgente atomica al rubidio (Rb) e sono utilizzati come backup del H-Maser qualora questi abbia un fermo per avaria o per manutenzione straordinaria (vedi fig. 6).
I 2 standard di frequenza secondari a vapori di Rubidio (Rb) sono montati appaiati in rack 19” con un set meccanico dedicato, nella console del Laboratorio della stazione T&F. Si è preferito utilizzare questo tipo di campione rispetto a quelli al Cesio per il suo miglior rapporto costo verso la stabilità a corto termine (come richiesto in una tipica applicazione VLBI, non alle più alte frequenze osservative), come mostrato di seguito:

1. Stabilità <2 E-11 @ (1 s)

Short-term stability (Allan variance)	$<2\times10^{-11}$ (1 s) $<1\times10^{-11}$ (10 s) $<2\times10^{-12}$ (100 s)

2. Purezza spetrale -103 dBc/Hz @ (1Hz)



Phase noise (SSB)	<–130 dBc/Hz (10 Hz) <–140 dBc/Hz (100 Hz) <–150 dBc/Hz (1 kHz) <–155 dBc/Hz (10 kHz)

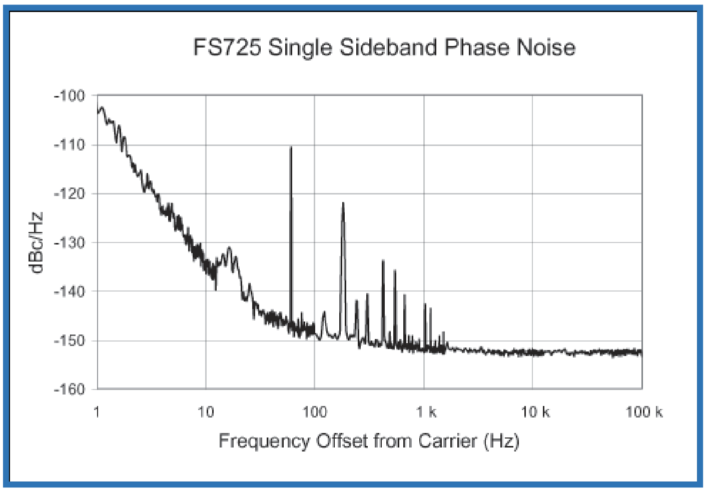


Fig. 6

I 2 standard di frequenza secondari a Rb montati appaiati in rack 19” con un set meccanico dedicato.

Generazione e distribuzione della scala di tempo locale

Abbiamo già accennato alla necessità di garantire una stretta coerenza fra il campione locale di frequenza (Maser o Rb) e la scala di tempo locale che controlla (soprattutto) il campionamento del segnale radioastronomico, se si vuole raggiungere la più alta risoluzione della tecnica VLBI.

Ecco perché l'impulso 1PPS (un Picco Per Secondo) è generato all'interno del campione di frequenza locale di stazione quando va distribuito a tutte le utenze "critiche" che richiedono questo livello di sincronizzazione. Per mantenere lo 1PPS locale molto prossimo al secondo UTC locale, si deve procedere allo "steering" (spostamento in tempo) INIZIALE di 1PPS locale, quale è ottenibile dalla messa in passo (sincronizzazione) con UTC locale, in pratica con 1PPS fornito da un buon ricevitore GPS, omologato per timing (come già descritto in precedenza). Dopo questo "scorrimento" iniziale è compito della stazione T&F monitorare, in continuo, lo scostamento del campione locale di frequenza con misure di Intervalli di Tempo (counter in start/stop) fra i vari impulsi 1PPS generati dai singoli campioni atomici rispetto alla scala GPS, assunta come riferimento comune da tutti gli Osservatori della rete VLBI (vedi rapporto interno IRA 517-18).
In base a misure oramai decennali, ci siamo convinti che misure ogni secondo, mediate su un'ora (24 campioni al giorno, registrati sia su disco locale che su database VLBEER) rappresentano un buon compromesso nell'accuratezza di misura delle derive storiche dei nostri campioni di frequenza. In questo modo contiamo di poter ripartire con un'ottima stima del tempo UTC locale, anche dopo un guasto del primo riferimento locale.

Altri tipi (non VLBI) di acquisizione digitale di segnali radioastronomici (o similari) hanno requisiti di sincronizzazione simili, ma non hanno questo requisito così stringente. Fra queste, prima fra tutte, è la movimentazione dell'antenna. In questo caso la risoluzione temporale va legata alla direttività dell'antenna alla frequenza di lavoro, al fine di mantenere la radiosorgente in osservazione (tracking) nel massimo di risposta dell'antenna (1/10 del beam), nonostante la rotazione della Terra. La scala di tempo che tiene conto della posizione angolare istantanea della Terra, prende il nome di UT1, non UTC quindi. Quest'ultima è mantenuta entro +/- 1s da UT1, con l'introduzione del cosiddetto secondo scalare (Leap second) e la differenza prevista fra loro è pubblicata in anticipo dal BPIM di Parigi. Solo nel caso dei prossimi ricevitori sopra 100GHz sarà necessario tenere conto di tale correzione.

Attualmente il laboratorio T&F è dotato di un dispositivo in grado di fornire sulla ***rete ethernet locale*** (server NTP IP: 192.168.189.33) la completa "time stamp" in formato NTP (Network Time Protocol).
L'apparato è altresì dotato di altre possibilità attualmente non utilizzate tra cui il formato PTP (Precision Time Protocol) che potrebbe arrivare a sincronizzare apparati meglio del microsecondo (<1μs) utilizzando una rete-ethernet dedicata. (Vedi fig. 7).

Fig. 7

Fronte e retro dell’apparato Meinberger Lantime M3000 che funziona da server NTP e PTP

A questo punto nello schema generale di fig. 8 che segue, possiamo riconoscere la gerarchia di distribuzione dei segnali di riferimento generati dall’H-MASER (5 MHz, 10 MHz ed 1PPS), tramite una serie di distributori della ditta TimeTech (fig.9), dei quali si riportano qui le caratteristiche principali e si rimanda agli allegati 3 e 4 per una completa consultazione.

Freq Dist Amp	**5MHz**	**10MHz**	**100MHz**
Gain variation Out-Out	**<0,1dB**		
Reverse isolation out-inp	**>140dB**		
Isolation Out-Out	**>120dB**	**>120dB**	**>110dB**
Group Delay 1-100MHz	**4,8ns**		
Group Delay variation vs. temp	**< 6ps/°k**		

Pulse Distribution Unit	**1PPS to 200MHz**
Rise / Fall Time	**<500ps**
Added Jitter	**<2ps**
Out-Out skew	**<20ps**
Instrument absolute delay	**<6,5ns nom.**
Temperature coefficient	**6ps/°k**

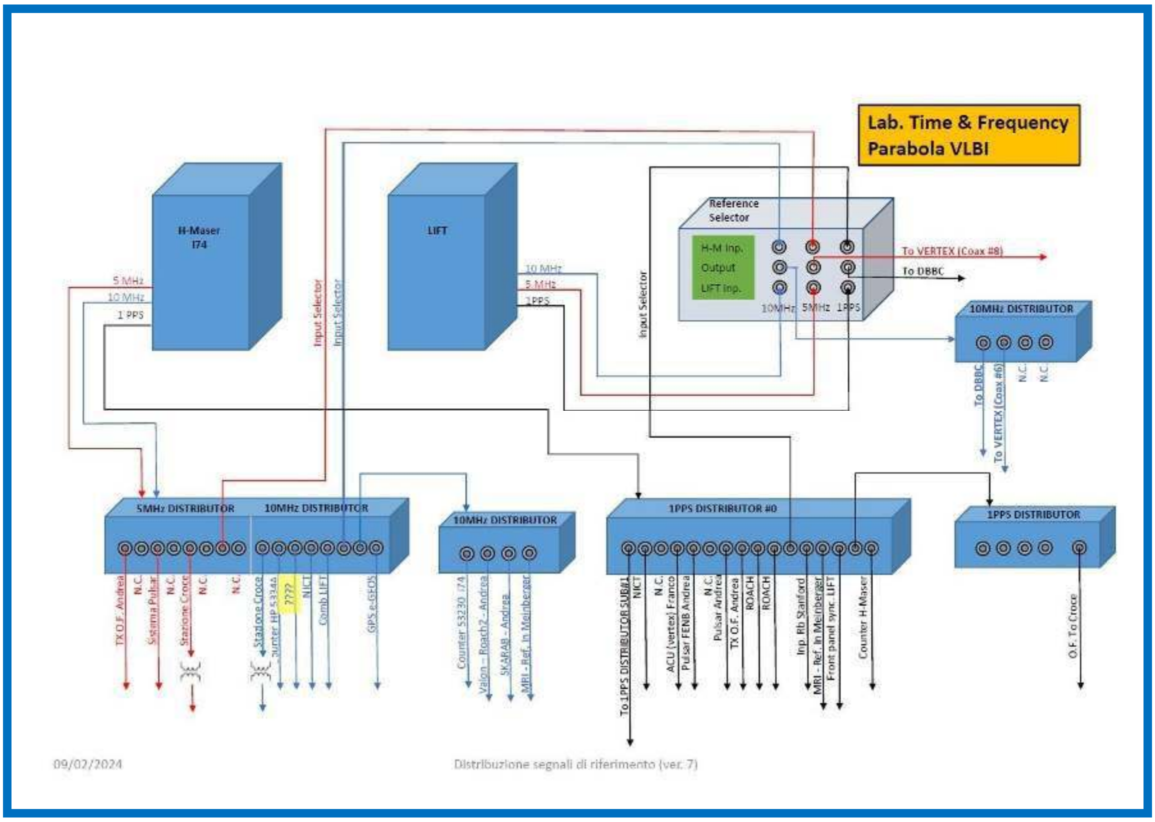


Fig. 8

Schema principale della distribuzione dei riferimenti 5MHz 10MHz e 1PPS
del Lab. T&F alla parabola VLBI (Vedi allegato 6).

Fig. 9

Distributori principali dei segnali di riferimento della ditta TimeTech.

Si ritiene opportuno menzionare che tutti questi apparati sono stati scelti e testati in laboratorio per verificarne le caratteristiche peculiari che li qualificano come apparati da laboratorio metrologico: tutte le uscite sono equalizzate in ampiezza e fase; manifestano un elevatissimo isolamento tra tutte le uscite (adiacenti o meno), ma anche tra uscite-ingresso.

Entrambe le uscite 5 MHz (A5) e 10 MHz (B1) del distributore principale, riportano come visibile nello schema, un trasformatore di isolamento (MiniCircuits mod. TMO-1-1T+) montato in linea, con la finalità di isolare galvanicamente i due collegamenti in cavo coassiale da 1" (un pollice) tra la palazzina parabola VLBI e la Stazione Radioastronomica "Croce del Nord". In caso di guasti, a questi trasformatori si può accedere dal cunicolo di collegamento tra la palazzina ed il basamento della parabola in corrispondenza del muro a sud della palazzina.

Le uscite 5 MHz (A7) e 10 MHz (B6), sempre del distributore principale, assieme al 1PPS prelevato dall'uscita out 11 del relativo distributore principale, sono collegate all'ingresso "privilegiato" (H.M. Input) dell'apparato denominato Reference Selector (che verrà descritto in un prossimo rapporto tecnico).
Per il riferimento 10MHz, avendo necessità di fornire 2 segnali uscenti, è stato necessario riutilizzare un distributore auto-costruito che ha già operato egregiamente per anni come distributore primario di tutta la stazione. (Vedi figura 11)
Tale dispositivo è stato costruito per poter selezionare anche remotamente due sistemi di generazione dei segnali di riferimento: lo H-MASER come sistema privilegiato o il sistema LIFT (The Italian Link for Time and Frequency) in occasione di osservazioni specifiche. (Vedi Fig. 10)

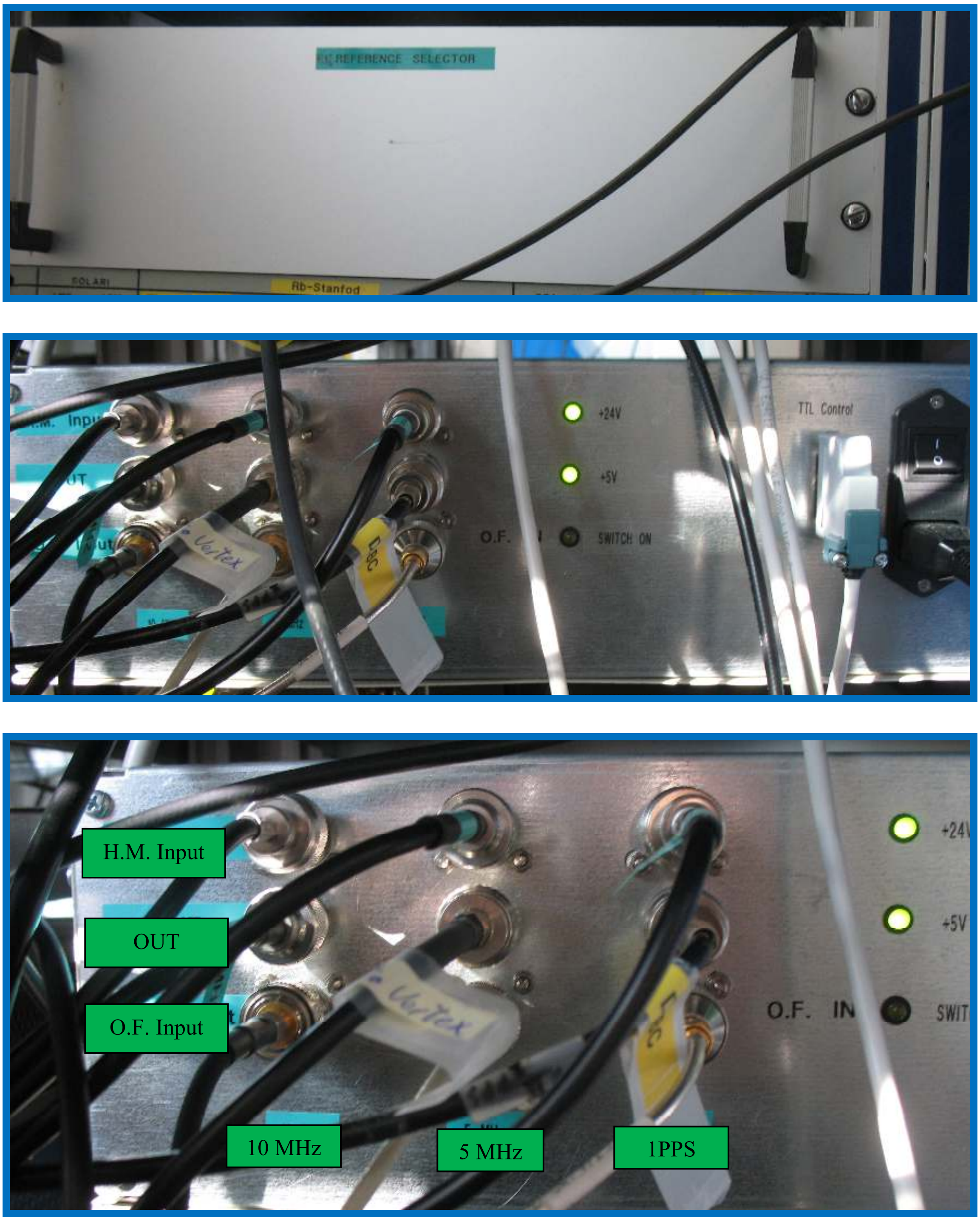


Fig. 10

Vista del frontale del retro e il particolare della parte connessioni.
In alto da sinistra a destra 10 e 5MHz e 1PPS del MASER, in basso i relativi ingressi del LIFT.
In centro le uscite che servono tutta la catena ricevente della parabola VLBI.

Le uscite del Reference Selector costituiscono i riferimenti che vengono utilizzati per l'intera catena, dal ricevitore al back-end, durante tutte le osservazioni che vengono svolte con la parabola VLBI.

Non ci si sofferma su tutti i singoli collegamenti agli apparati utenti individuabili e visibili nel grafico di Fig. 8, ma si mette in evidenza l'uscita out15 del **1PPS distributor**. Questa va ad alimentare un secondo distributore di 1PPS la cui ultima uscita si presenta in fibra ottica su connettore ST (fibra 62,5/125 o anche 50/125 multimodale) per interfacciarsi e trasferire quindi il segnale di riferimento alla palazzina "Croce del Nord". (Vedi Fig. 11)

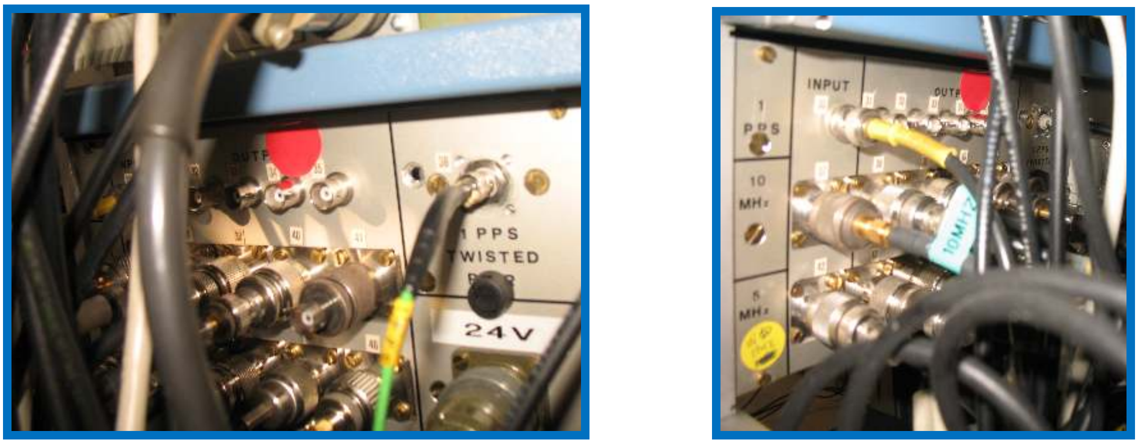


Fig. 11

Vista del distributore supplementare del 1PPS con uscita in fibra ottica e Ex distributori primari 5 e 10 MHz.

Si fa notare che gli apparati alloggiati nelle console ed alimentati a 24Vdc sono molto aumentati nel tempo, di conseguenza s'è reso necessario realizzare una distribuzione di questa alimentazione in continua e si approfitta di questa occasione per documentarla. (Fig.12)

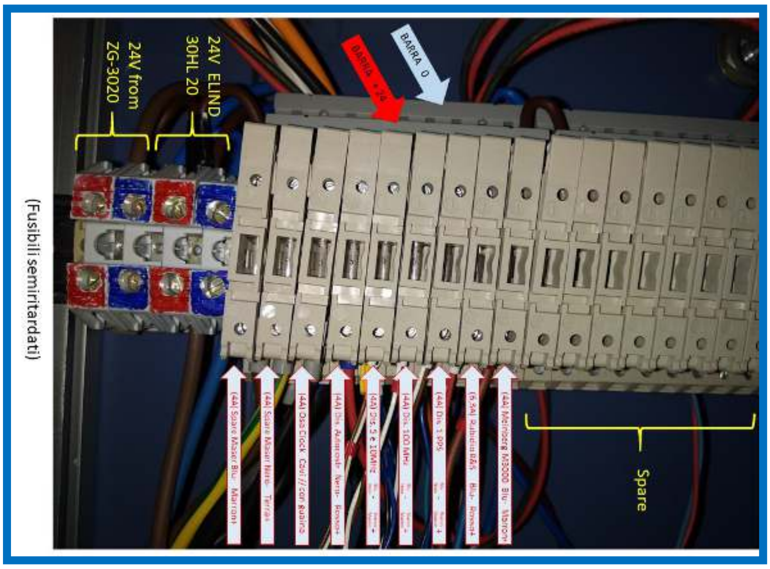


Fig.12

Particolare della distribuzione 24Vdc agli apparati utilizzatori con riportato il valore del corrispondente fusibile utilizzato a protezione.

Come precedentemente menzionato questa attenzione alla ridondanza delle alimentazioni che può sembrare quasi “maniacale”, di fatto è ciò che ha permesso di raccogliere dati continui per almeno 11 anni e per 9 anni senza apportare nuove sincronizzazioni che avrebbero interrotto la sequenza temporale, ma solo correzioni di frequenza, di quantità note, in unità calibrate. Vedi andamento storico del ritardo GPS-H MASER. (Vedi Fig. 13)

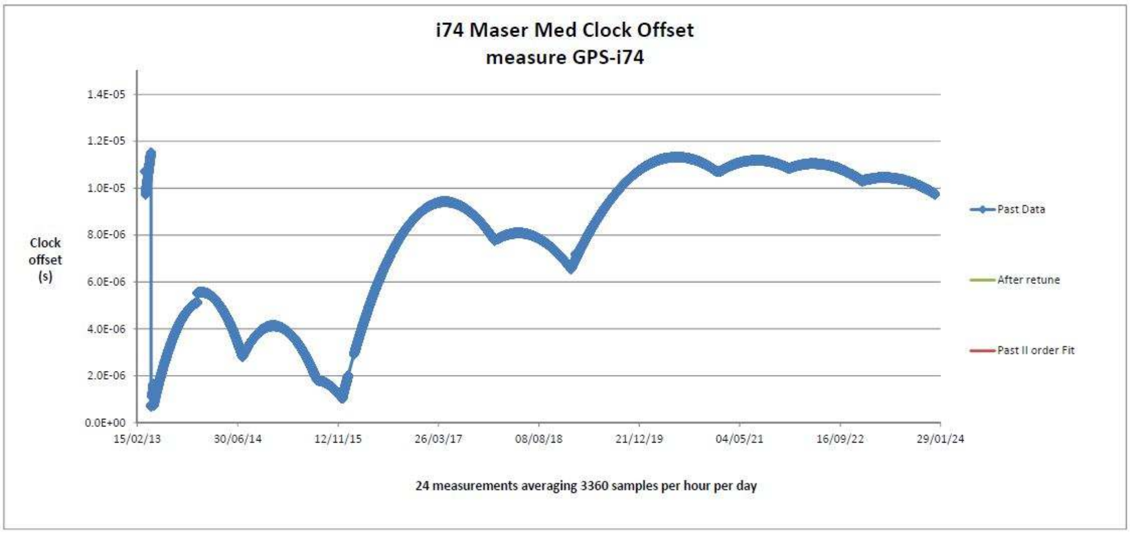


Fig. 13

Andamento storico delle misure GPS – I74 Maser

Il grafico di figura 13 riassume la storia del nostro Maser i74, in pratica qui sono riportate 24 misure giornaliere per 11 anni consecutivi di funzionamento senza alcuna interruzione di continuità.

Le singole misure (1 di 24) sono poi il risultato della media ottenuta dal campionamento ogni secondo di 3360 misure del clock offset (GPS-i74), raccolte da un time interval counter dedicato .

Come ben visibile ad inizio del grafico ed a fine 2013 inizio 2014 si possono notare discontinuità dell’andamento, ebbene queste sono dovute ad operazioni di riallineamento del 1PPS locale al 1PPS UTC tramite operazioni di nuove sincronizzazioni.

Nel restante periodo si è operato solamente su aggiustamenti “dell’oscillazione” (parti in 10^{-13}), tali da portarci a lavorare nell’intorno dei -10µs (microsecondi di ritardo). Tale margine di sicurezza ci garantisce periodi molto lunghi (ordine dell’anno) per non incorrere in misure GPS-i74 complementari ad 1: esempio il 1PPS di i74 arriva prima del 1PPS del GPS, la lettura che otterremo con il time interval counter non sarà più 10µs ma 0,999.990s.

(Vedi anche [1][2])

La distribuzione di Tempo & Frequenza alla Stazione “Croce del Nord”

E’ dal finire degli anni ’80 che si è provveduto a trasferire i segnali di riferimento del H-MASER alla Stazione “Croce del Nord” per utilizzarli nelle osservazioni con questo radiotelescopio.
Gli apparati furono progettati e costruiti per ripristinarne le perdite di segnale subite nel percorso dalla parabola alla stazione e quindi compatibili con i moderni distributori commerciali.
Si vuol sottolineare che gli arrivi sono localizzati in posti diversi come riportato nello schema seguente (fig. 14): i terminali dei cavi coassiali in arrivo sono individuabili sotto il pavimento galleggiante nel corridoio armadi ex movimentazione Est-Ovest (vedi fig. 16), mentre il 1PPS in fibra ottica ha l’arrivo nel rack che alloggia anche l’ingresso della rete ethernet ed è ben individuabile come out#3. Viene poi collegato ad una fibra di colore verde 62,5/125, che trasporta il segnale all’apparato ricevente alloggiato nella stanza ricevitore “Croce del Nord”. Vedi fig. 15

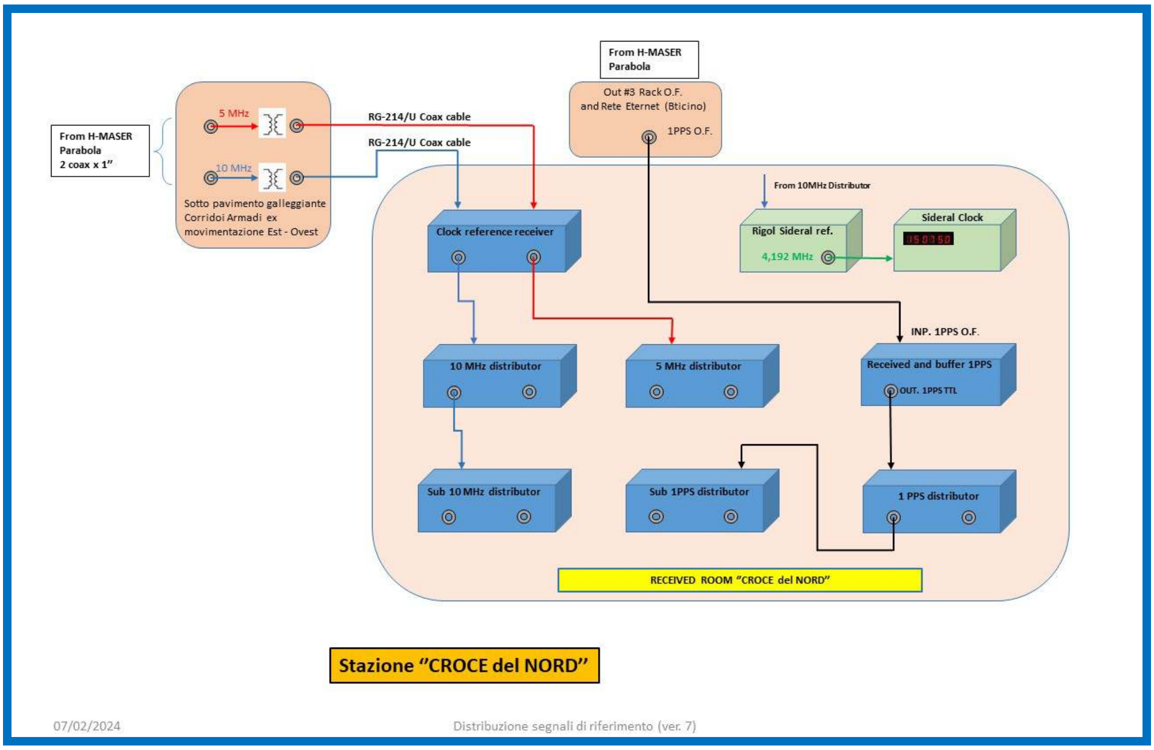


Fig. 14

Schema arrivi ed apparati di distribuzione della stazione “Croce del Nord”

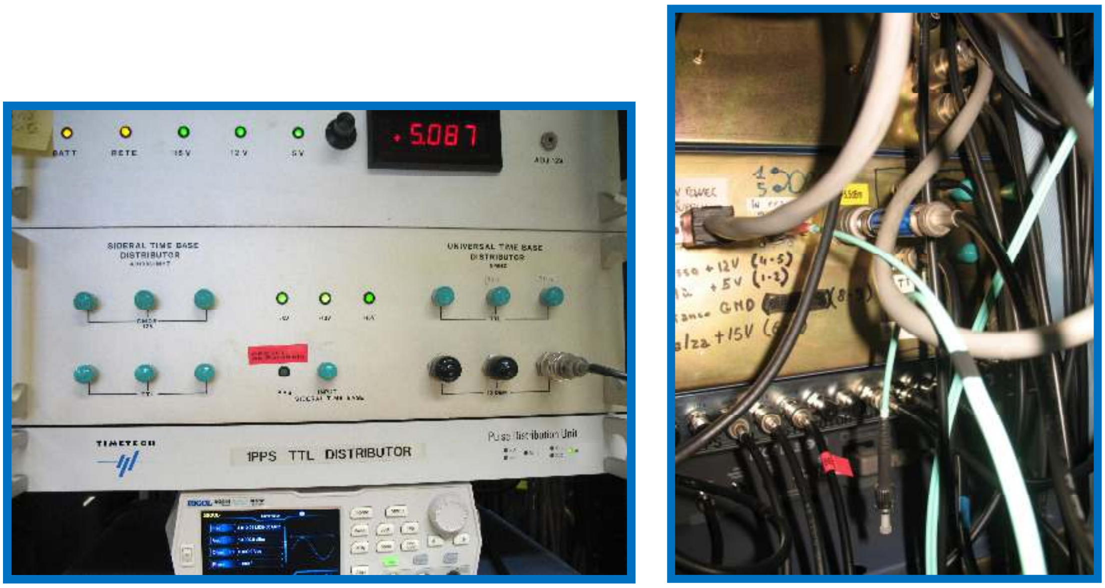


Fig. 15

Fronte e retro dell'apparato che alloggia il ricevitore in fibra ottica del 1PPS del MASER

Fig. 16

Arrivi dei 2 cavi da 1" che trasportano i segnali 5 e 10 MHz.

I segnali di riferimento a 5MHz e 10MHz che partono dal laboratorio T&F, arrivano alla palazzina Croce mediante cavo coassiale da 1pollice lungo circa 600m. e terminano con ulteriori 2 trasformatori d'isolamento (MiniCircuits mod. TMO-1-1T+); da qui tramite cavi coassiali flessibili diametro 11mm. (alias RG 214/U), arrivano all'ingresso dell'apparato "Clock Reference Receiver" alloggiato nella stanza ricevitore "Croce del Nord". Vedi fig. 17 e 18

Fig. 17

Particolare dei 2 arrivi 5 e 10 MHz con i relativi trasformatori alloggiati in contenitori isolati.

Il “Clock Reference Receiver” provvede a ripristinare i livelli di partenza dei riferimenti riportandone la potenza RF a +12 dBm (Fig. 18) e le sue uscite vanno ad alimentare i distributori principali di riferimento della stanza ricevitore “Croce” da cui si ripartono le varie utenze.

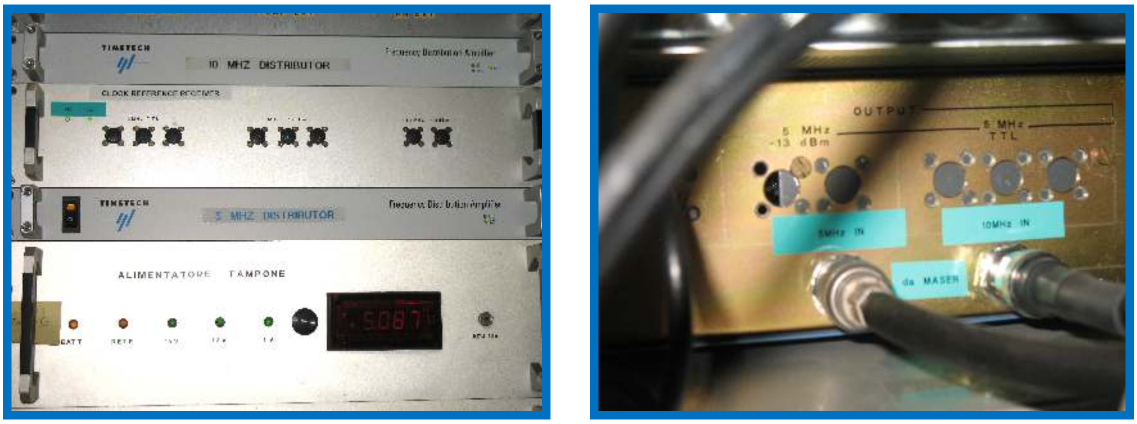


Fig. 18

Fronte e retro dell’apparato “Clock Reference Receiver”

Vista l'alta richiesta di riferimenti a 10MHz e 1PPS per la sincronizzazione, si è reso necessario integrare la distribuzione all'interno della stanza ricevitore "Croce", con ulteriori apparati di distribuzione denominati SUB e che verranno alloggiati il più vicino possibile alle apparecchiature che necessitano di tali riferimenti. Vedi Fig. 19

Fig. 19

Non si riportano qui i collegamenti agli apparati poiché a breve la stanza verrà rimodulata profondamente e sarà quello il momento per una ridefinizione anche della distribuzione capillare agli apparati.

Da ultimo si riporta l'immagine completa del rack che alloggia sia gli apparati di ricezione trattamento dei segnali, sia i distributori principali 5MHz, 10MHz e 1PPS e gli orologi di stazione. Vedi Fig. 20

Fig. 20

Considerazioni finali

La continua richiesta di fornire nuovi segnali di riferimento, in particolar modo 10MHz e 1PPS, deve essere motivo di un continuo studio preventivo dell'evoluzione della stazione, anticipando la disponibilità per futuri utilizzatori, lasciando un buon numero di connettori ancora liberi.
Segnaliamo l'opportunità di mantenere sempre una scorta anche dei nuovi modelli di distributori utilizzati, per una loro rapida sostituzione nel caso di guasti. A tal proposito segnalo che le uniche due avarie che si sono verificate su apparati TimeTech hanno riguardato solo i loro alimentatori interni.

Gli autori restano a disposizione per ulteriori informazioni. Speriamo di aver mostrato come il laboratorio di T&F sia fondamentale per il funzionamento tanto della parabola VLBI come della Croce del Nord. Si precisa però che *non va preso per scontato* il suo corretto funzionamento per molti anni ancora, senza almeno gli stessi continui controlli (Vedi [1][2]), studi, dedizione e sviluppi da noi applicati.

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e presente nella vetrina del Lab. T&F

[10] LIFT (The Italian Link for Time and Frequency)
Published in: 2013 Joint European Frequency and Time Forum & International Frequency Control Symposium (EFTF/IFC)
21-25 July 2013
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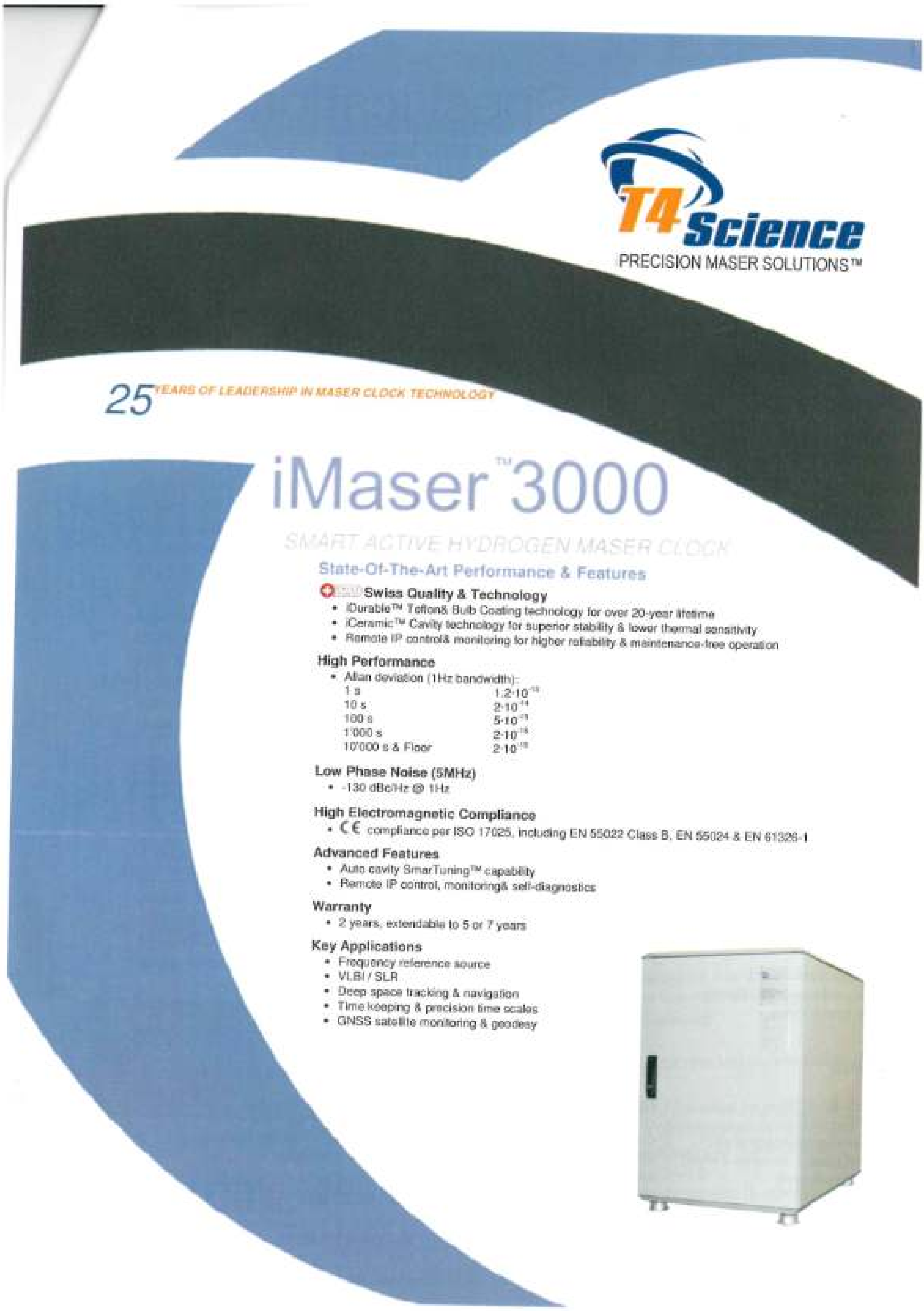
Ringraziamenti

Si ringrazia il Ing. ORLATI Andrea per aver svolto la funzione di revisore.

Seguono allegati:

Allegato 1



T4Science
PRECISION MASER SOLUTIONS™

25 YEARS OF LEADERSHIP IN MASER CLOCK TECHNOLOGY

iMaser™ 3000

SMART ACTIVE HYDROGEN MASER CLOCK

State-Of-The-Art Performance & Features

Swiss Quality & Technology
- iDurable™ Teflon& Bulb Coating technology for over 20-year lifetime
- iCeramic™ Cavity technology for superior stability & lower thermal sensitivity
- Remote IP control& monitoring for higher reliability & maintenance-free operation

High Performance
- Allan deviation (1Hz bandwidth):

1 s	$1.2\cdot10^{-13}$
10 s	$2\cdot10^{-14}$
100 s	$5\cdot10^{-15}$
1'000 s	$2\cdot10^{-15}$
10'000 s & Floor	$2\cdot10^{-15}$

Low Phase Noise (5MHz)
- -130 dBc/Hz @ 1Hz

High Electromagnetic Compliance
- CE compliance per ISO 17025, including EN 55022 Class B, EN 55024 & EN 61326-1

Advanced Features
- Auto cavity SmarTuning™ capability
- Remote IP control, monitoring& self-diagnostics

Warranty
- 2 years, extendable to 5 or 7 years

Key Applications
- Frequency reference source
- VLBI / SLR
- Deep space tracking & navigation
- Time keeping & precision time scales
- GNSS satellite monitoring & geodesy

iMaser™ 3000 Specifications

STABILITY

•Allan deviation (1Hz bandwidth):		LN Option
1 s	$1.5\cdot10^{-13}$	$1.2\cdot10^{-13}$
10 s	$2\cdot10^{-14}$	$2\cdot10^{-14}$
100 s	$5\cdot10^{-15}$	$5\cdot10^{-15}$
1'000 s	$2\cdot10^{-15}$	$2\cdot10^{-15}$
10'000 s	$2\cdot10^{-15}$	$2\cdot10^{-15}$

ENVIRONMENTAL

•Temperature sensitivity	$<5\cdot10^{-15}$ /K	
•Phase sensitivity to temperature (between sine outputs)	10 ps/K	
•Magnetic sensitivity	$<1\cdot10^{-13}$ /G	
	$<3\cdot10^{-14}$ /G	(Option: MS)
•Frequency sensitivity to vibration	$<1\cdot10^{-9}$ /g	
•Power source sensitivity:	$<1\cdot10^{-14}$ /V	

CONTROL

• Synthesized frequency resolution	$6.4\cdot10^{-19}$
• Frequency tuning range	$\pm 3\cdot10^{-8}$

OUTPUTS

• 5 MHz	2	
• 10 MHz	4	(Option: O4)
• 100 MHz	2	
• 1 PPS TIMING	1	

SINE OUTPUT SIGNALS

	5 / 10 / 100 MHz	
• Level (50 Ω)	13	dBm
• Isolation	80	dB
• Spectral purity (2nd harmonic)	-40	dBc
• Spectral purity (spurious)	-70	dBc

1 PPS TIMING

	Output	Input
• Format (I/O)	1 PPS (1 Out)	1 PPS (1 In)
• Amplitude (TTL compatible)	3 V (50 Ω)	3 V (50 Ω)
• Pulsewidth	100 µs	>100 ns
• Rise time	<4 ns	<1 µs
• Jitter	<100 ps	<1 µs
• Auto sync Input		1 PPS
• User settable (software / Ethernet)		50 ns/step
• Sync Input to Output		< 25 ns

POWER

• DC	22 to 30V (3 A typical)	
• AC (50-60Hz)	220 V (176 - 264 V)	
	110 V (85 - 135 V)	(Option: 110V)
• Power normal operation /(Peak)	100 W / (220 VA max)	
• Power (standby: ion pumps & heater)	<30 W Standby battery operation	
• Battery pack (UPS)	24V (Approved for air transport IATA)	
	18 hours	(Option: BAT1)
	36 hours	(Option: BAT2)

PHASE NOISE

Output	5 MHz (dBc/Hz)	
	Standard	Option LN
1 Hz	-117	-130
10 Hz	-135	-142
100 Hz	-145	-152
1 kHz	-152	-156
10 kHz	-155	-156
100 kHz	-155	-156

Output	10 MHz (dBc/Hz)	
	Standard	Option LN
1 Hz	-109	-121
10 Hz	-129	-135
100 Hz	-139	-145
1 kHz	-146	-150
10 kHz	-149	-150
100 kHz	-149	-150

Output	100 MHz (dBc/Hz)	
	Standard	Option LN
1 Hz	-89	-100
10 Hz	-105	-113
100 Hz	-115	-120
1 kHz	-125	-148
10 kHz	-145	-151
100 kHz	-145	-151

ADVANCED FEATURES

- Auto cavity SmarTuning™ (Option: CT)
- Remote Ethernet control & monitoring (Option: RE)

ELECTROMAGNETIC COMPLIANCE

- CE compliance per ISO 17025, including EN 55022 Class B, EN 55024 & EN 61326-1

MECHANICAL

• Size (WxDxH)	60x80x95 cm 23.7 x31.5 x37.5"
• Weight	100kg/220lb (without battery packs) Add 40 kg / 88 lb per battery pack

WARRANTY

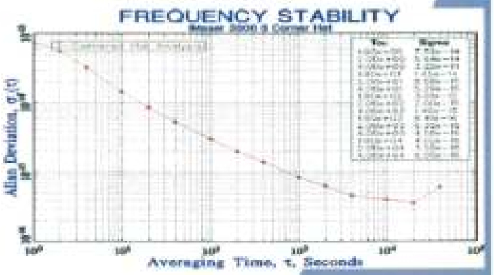
- 2 years
- Extendable to 5 or 7 years (Option: W5 or W7)

ORDERING

- Instructions Maser / xx/ xx / xx (xx = option codes)

Example: Maser BAT2/O4/110V/LN/RE/W5)

TYPICAL STABILITY



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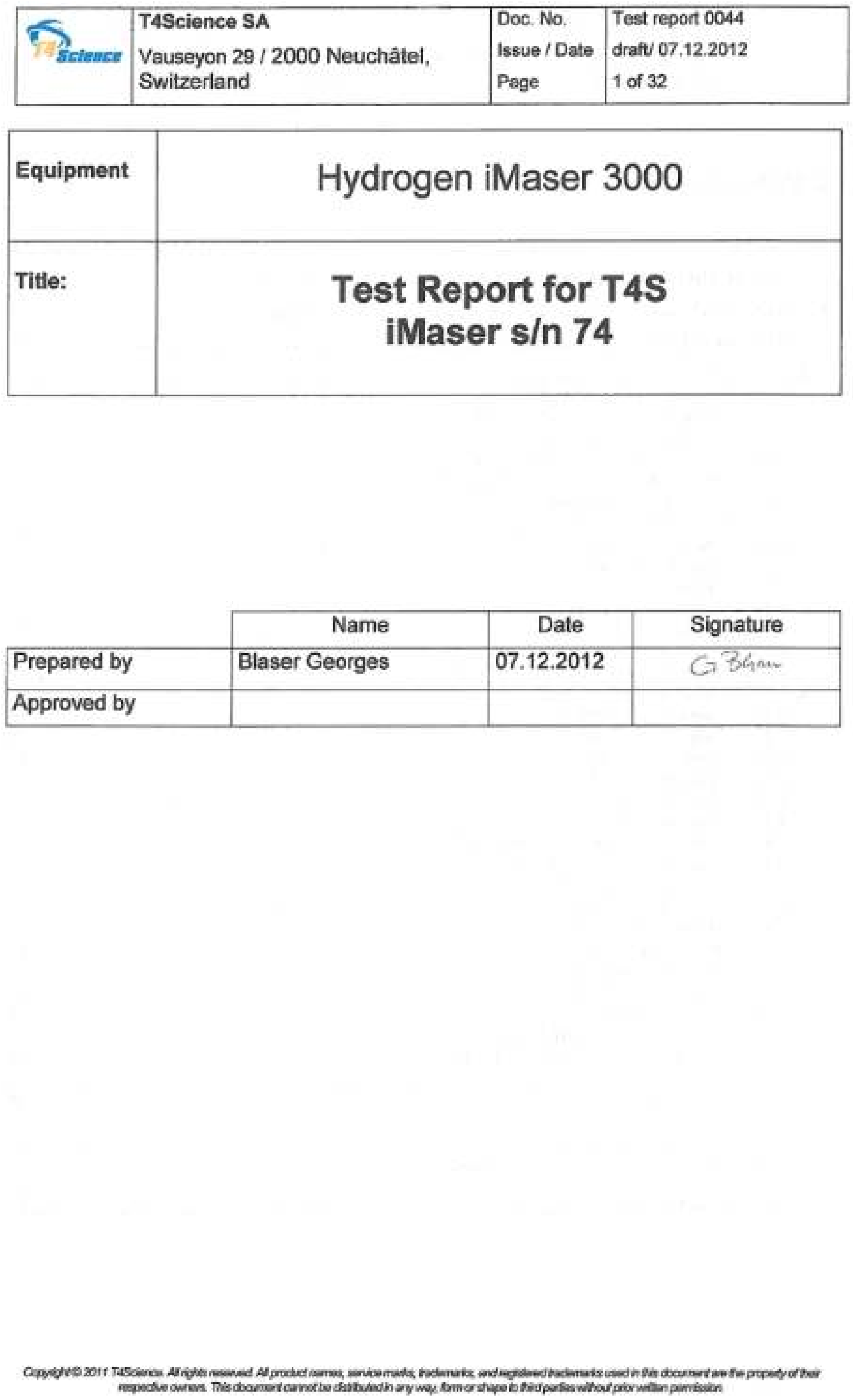
Allegato 2



	T4Science SA Vauseyon 29 / 2000 Neuchâtel, Switzerland	Doc. No. Issue / Date Page	Test report 0044 draft/ 07.12.2012 1 of 32

Equipment	Hydrogen iMaser 3000
Title:	**Test Report for T4S iMaser s/n 74**

	Name	Date	Signature
Prepared by	Blaser Georges	07.12.2012	
Approved by			

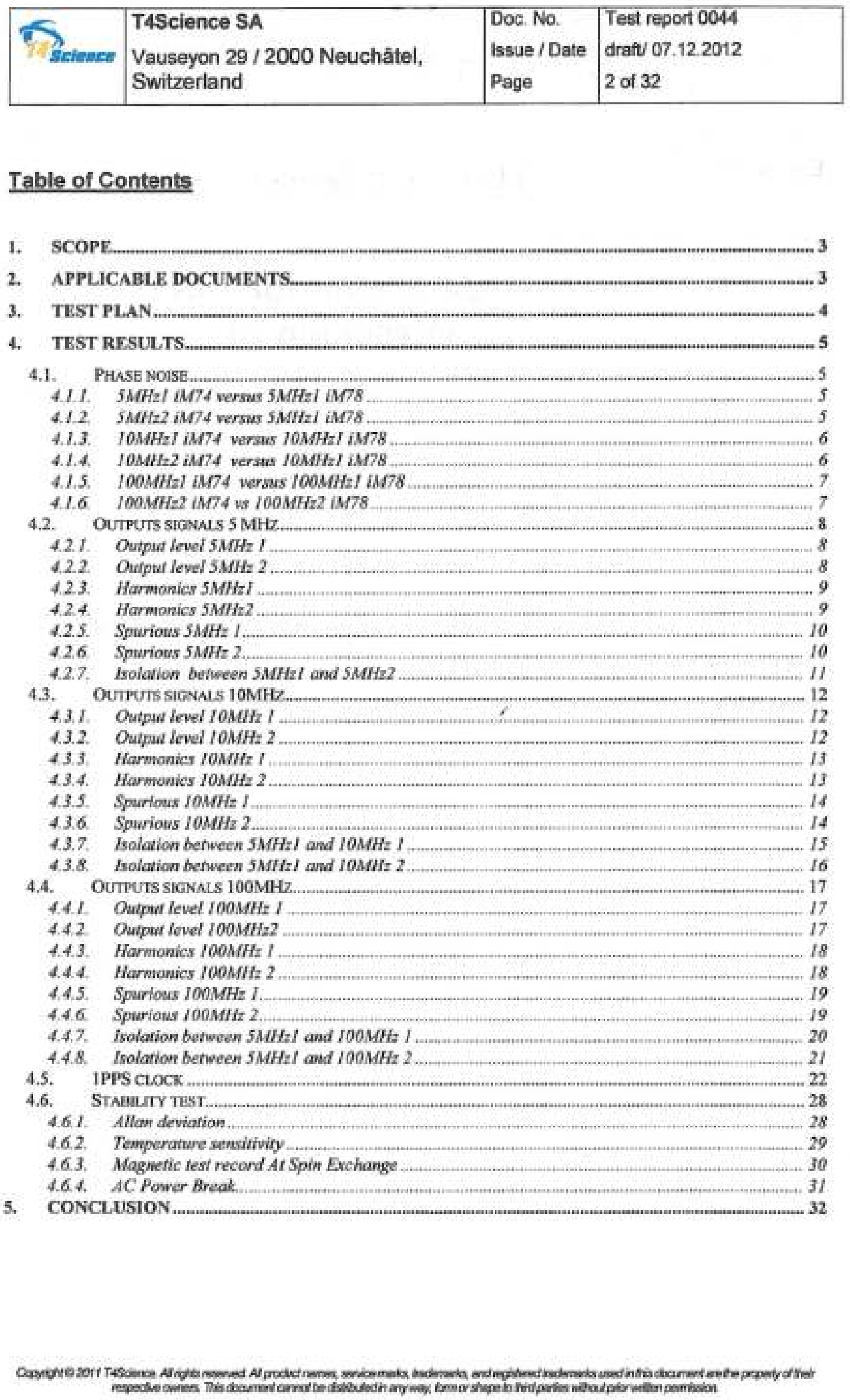


Table of Contents

1. Scope

This document summarizes the factory acceptance procedure of the Hydrogen Masers measuring results.

2. Applicable Documents

AD1: Order no 20885

3. Test plan

PHASE NOISE

5MHz 1 and 2 iM74 vs 5MHz 1 and 2 iM78
10MHz 1and 2 iM74 vs 10MHz1 iM78
100MHz 1 and 2 iM74 vs 100MHz 1 and 2 iM78

OUTPUTS SIGNALS 5 MHZ

Output level 5MHz 1 and 2
Harmonics 5MHz 1 and 2
Spurious 5MHz 1 and 2
Isolation 5MHz 1 and 2

OUTPUTS SIGNALS 10 MHZ

Output level 10MHz 1 and 2
Harmonics 10MHz 1 and 2
Spurious 10MHz 1 and 2
Isolation 10MHz 1 and 2

OUTPUTS SIGNALS 100 MHZ

Output level 100MHz 1 and 2
Harmonics 100MHz 1 and 2
Spurious 100MHz 1 and 2
Isolation 100MHz 1 and 2

1PPS CLOCK

STABILITY TEST

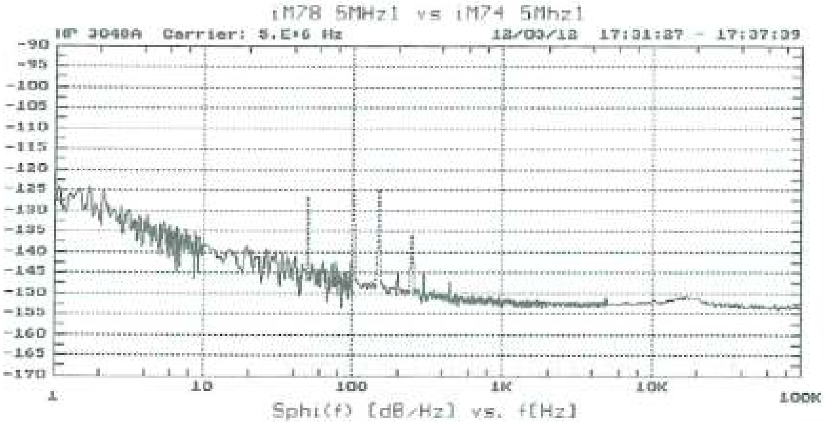
Allan deviation
Temperature sensitivity
Magnetic test record
AC power break

4. Test results

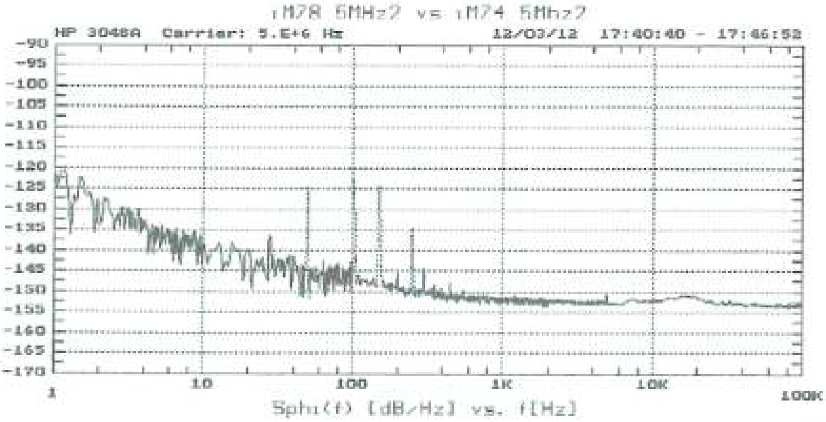
4.1. Phase noise

The phase results are raw data value, so 3dB may be subtract due to the use of same unit type OCXO.

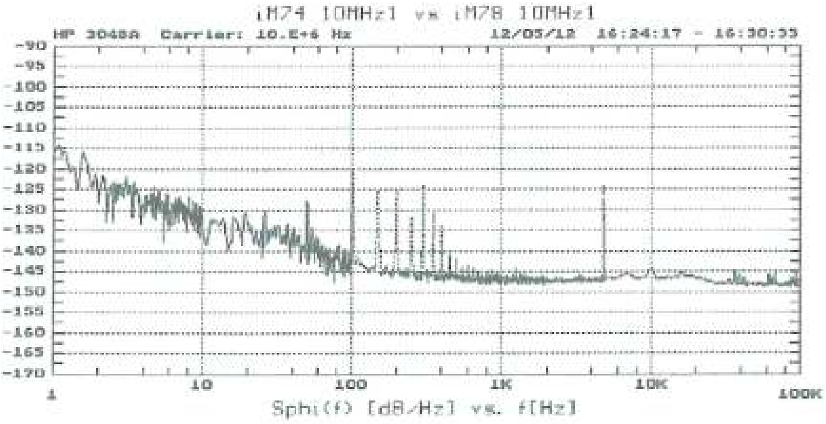
4.1.1. 5MHz1 iM74 versus 5MHz1 iM78



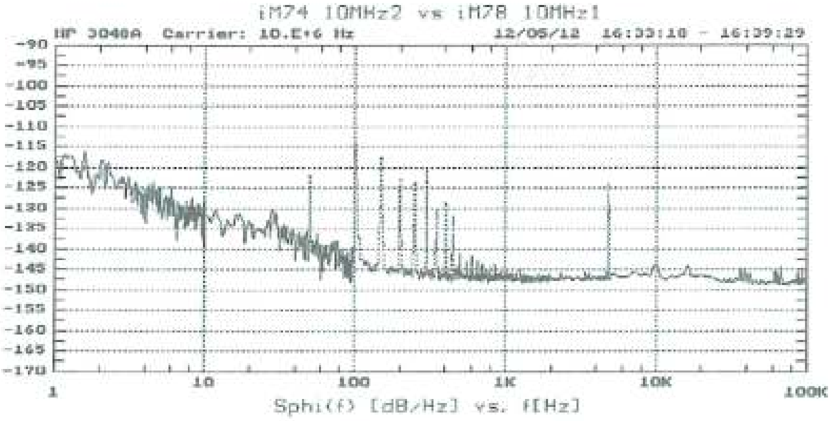
4.1.2. 5MHz2 iM74 versus 5MHz2 iM78



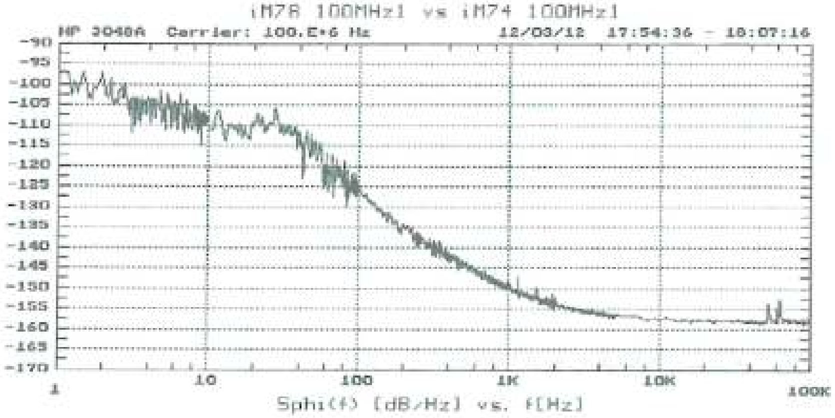
4.1.3. 10MHz1 iM74 versus 10MHz1 iM78



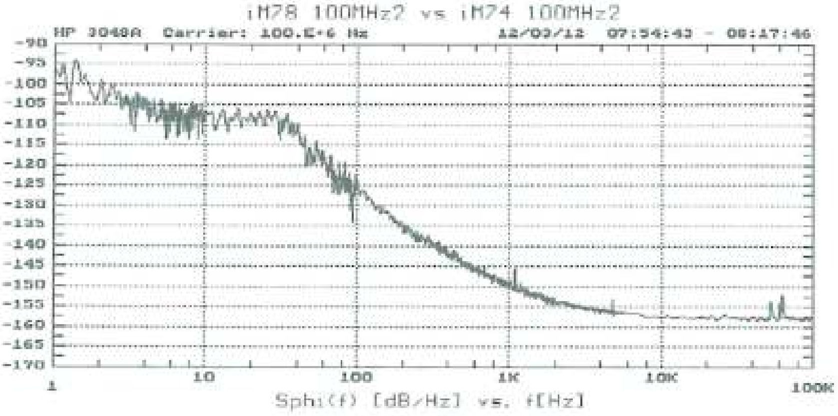
4.1.4. 10MHz2 iM74 versus 10MHz1 iM78



4.1.5. 100MHz1 iM74 versus 100MHz1 iM78

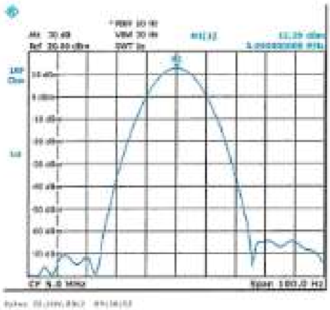


4.1.6. 100MHz2 iM74 vs 100MHz2 iM78



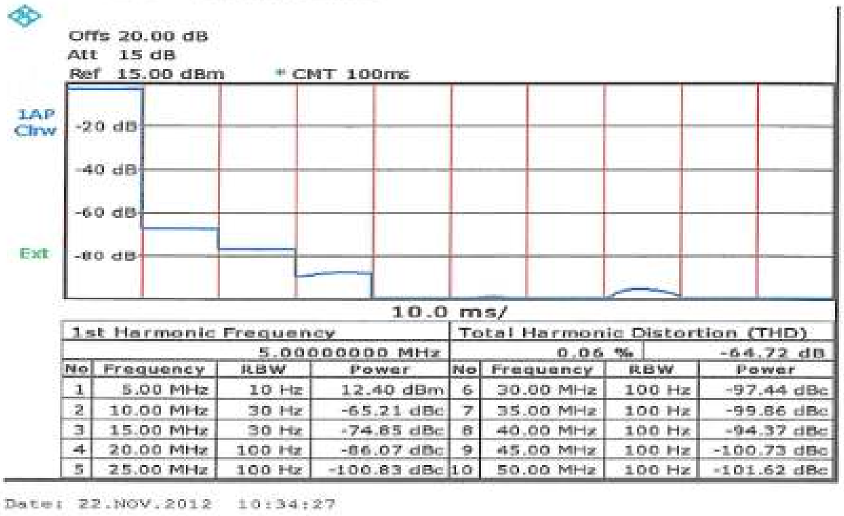
4.2. Outputs signals 5 MHz

4.2.1. Output level 5MHz 1



4.2.2. Output level 5MHz 2

4.2.3. Harmonics 5MHz1



1st Harmonic Frequency				Total Harmonic Distortion (THD)			
			5.00000000 MHz		0.06 %		-64.72 dB
No	Frequency	RBW	Power	No	Frequency	RBW	Power
1	5.00 MHz	10 Hz	12.40 dBm	6	30.00 MHz	100 Hz	-97.44 dBc
2	10.00 MHz	30 Hz	-65.21 dBc	7	35.00 MHz	100 Hz	-99.86 dBc
3	15.00 MHz	30 Hz	-74.85 dBc	8	40.00 MHz	100 Hz	-94.37 dBc
4	20.00 MHz	100 Hz	-86.07 dBc	9	45.00 MHz	100 Hz	-100.73 dBc
5	25.00 MHz	100 Hz	-100.83 dBc	10	50.00 MHz	100 Hz	-101.62 dBc

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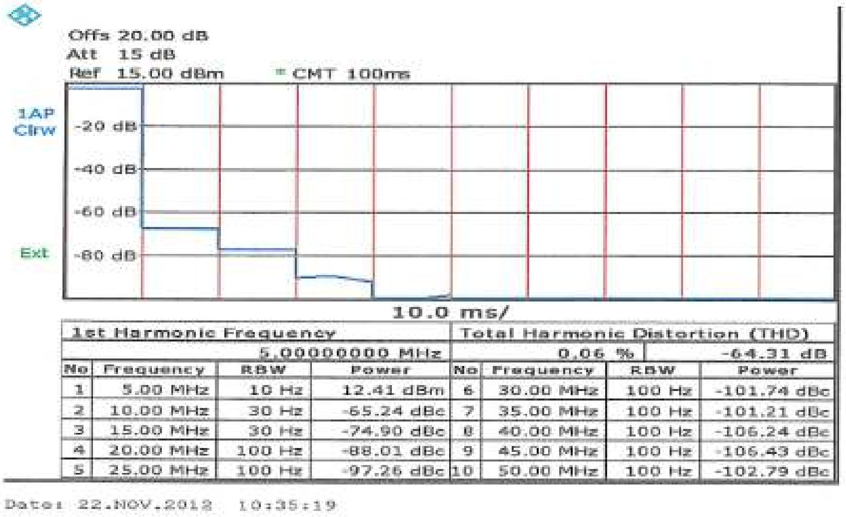
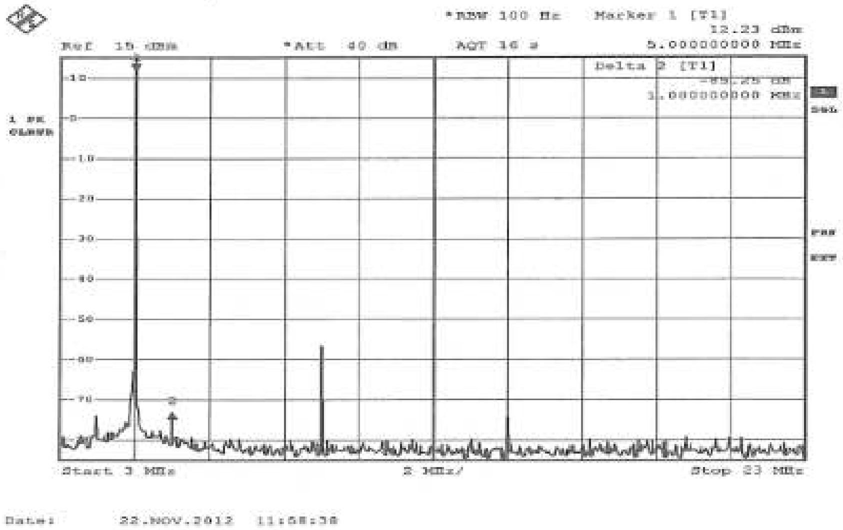
4.2.4. Harmonics 5MHz2



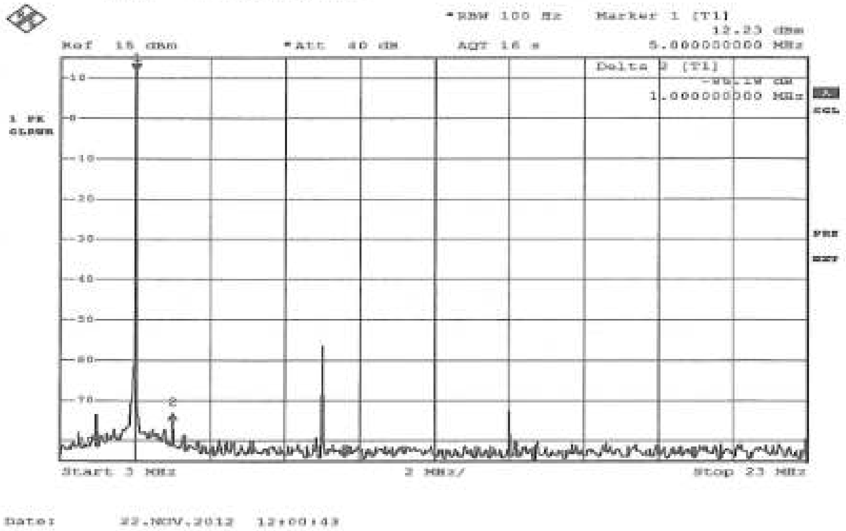
1st Harmonic Frequency				Total Harmonic Distortion (THD)			
			5.00000000 MHz		0.06 %		-64.31 dB
No	Frequency	RBW	Power	No	Frequency	RBW	Power
1	5.00 MHz	10 Hz	12.41 dBm	6	30.00 MHz	100 Hz	-101.74 dBc
2	10.00 MHz	30 Hz	-65.24 dBc	7	35.00 MHz	100 Hz	-101.21 dBc
3	15.00 MHz	30 Hz	-74.90 dBc	8	40.00 MHz	100 Hz	-106.24 dBc
4	20.00 MHz	100 Hz	-88.01 dBc	9	45.00 MHz	100 Hz	-106.43 dBc
5	25.00 MHz	100 Hz	-97.26 dBc	10	50.00 MHz	100 Hz	-102.79 dBc

Date: 22.NOV.2012 10:35:19

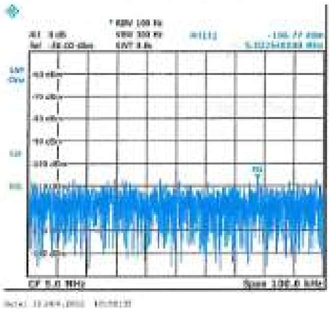
4.2.5. Spurious 5MHz 1



4.2.6. Spurious 5MHz 2



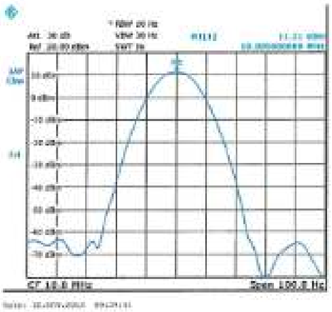
4.2.7. Isolation between 5MHz1 and 5MHz2



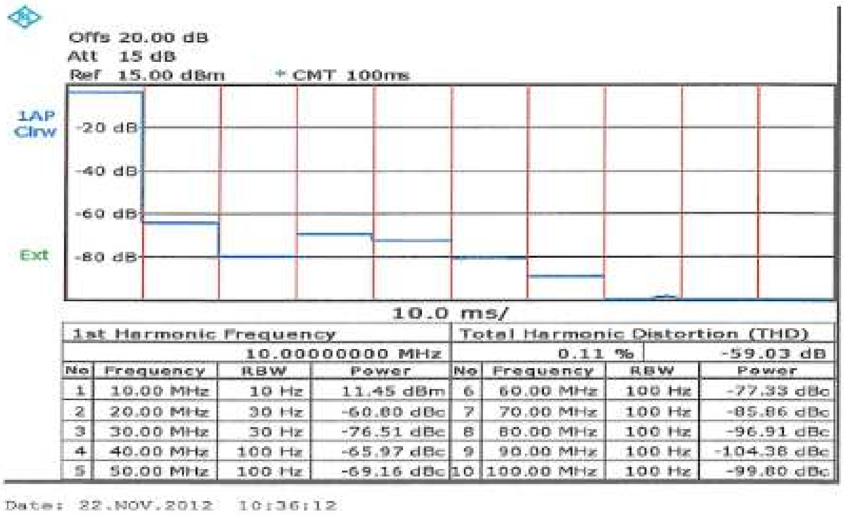
4.3. Outputs signals 10MHz

4.3.1. Output level 10MHz 1

4.3.2. Output level 10MHz 2



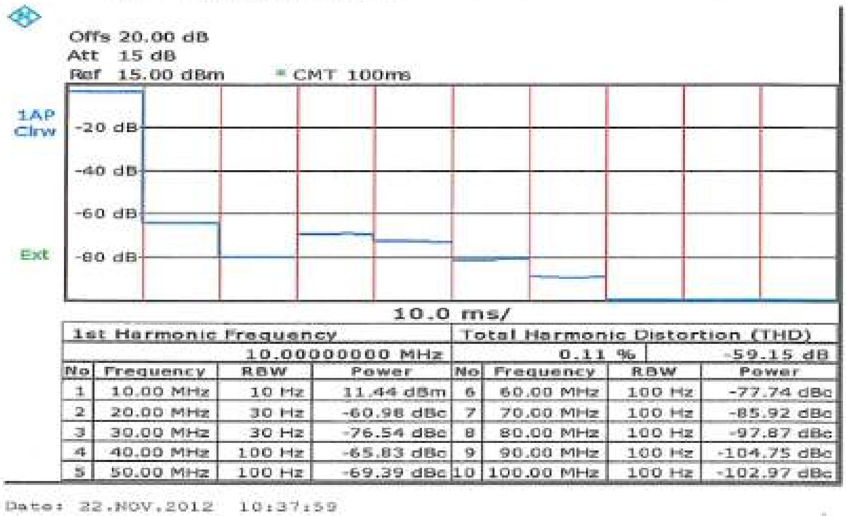
4.3.3. Harmonics 10MHz 1



1st Harmonic Frequency				Total Harmonic Distortion (THD)			
10.00000000 MHz				0.11 %		-59.03 dB	
No	Frequency	RBW	Power	No	Frequency	RBW	Power
1	10.00 MHz	10 Hz	11.45 dBm	6	60.00 MHz	100 Hz	-77.33 dBc
2	20.00 MHz	30 Hz	-60.80 dBc	7	70.00 MHz	100 Hz	-85.86 dBc
3	30.00 MHz	30 Hz	-76.51 dBc	8	80.00 MHz	100 Hz	-96.91 dBc
4	40.00 MHz	100 Hz	-65.97 dBc	9	90.00 MHz	100 Hz	-104.38 dBc
5	50.00 MHz	100 Hz	-69.16 dBc	10	100.00 MHz	100 Hz	-99.80 dBc

Date: 22.NOV.2012 10:36:12

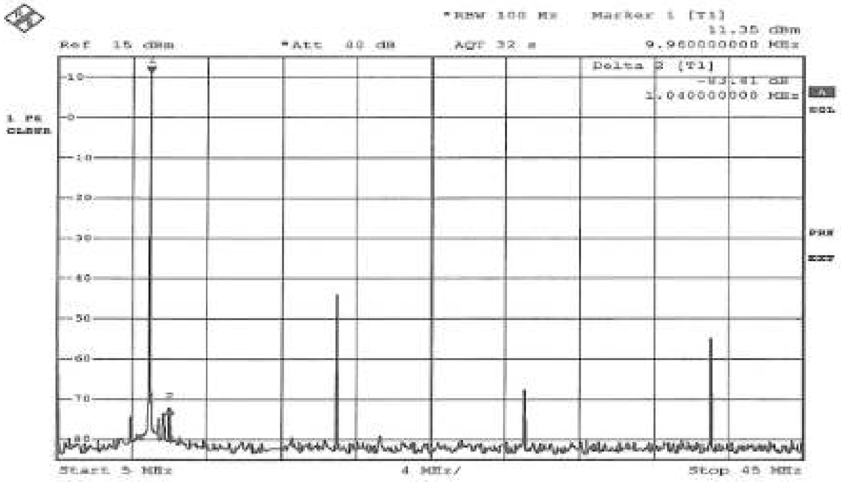
4.3.4. Harmonics 10MHz 2



1st Harmonic Frequency				Total Harmonic Distortion (THD)			
10.00000000 MHz				0.11 %		-59.15 dB	
No	Frequency	RBW	Power	No	Frequency	RBW	Power
1	10.00 MHz	10 Hz	11.44 dBm	6	60.00 MHz	100 Hz	-77.74 dBc
2	20.00 MHz	30 Hz	-60.98 dBc	7	70.00 MHz	100 Hz	-85.92 dBc
3	30.00 MHz	30 Hz	-76.54 dBc	8	80.00 MHz	100 Hz	-97.87 dBc
4	40.00 MHz	100 Hz	-65.83 dBc	9	90.00 MHz	100 Hz	-104.75 dBc
5	50.00 MHz	100 Hz	-69.39 dBc	10	100.00 MHz	100 Hz	-102.97 dBc

Date: 22.NOV.2012 10:37:59

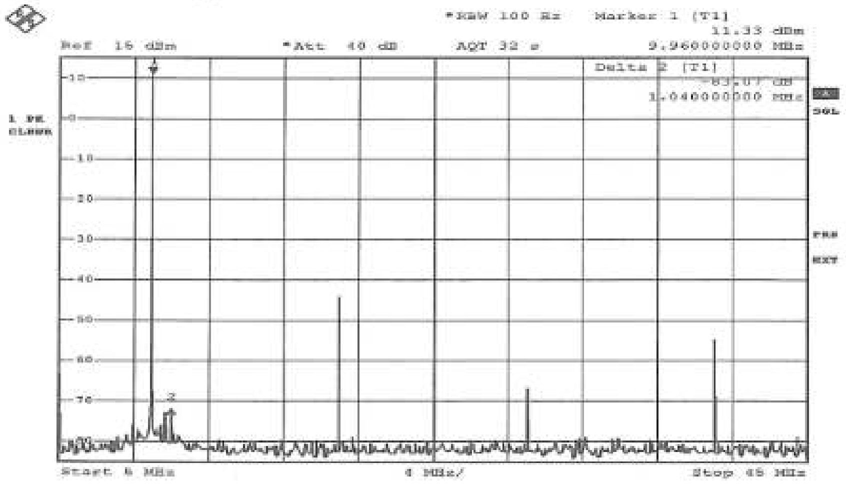
4.3.5. Spurious 10MHz 1



*RBW 100 Hz Marker 1 [T1]
11.35 dBm
Ref 15 dBm *Att 40 dB AQT 32 s 9.960000000 MHz
Delta 2 [T1]
-83.81 dB
1.040000000 MHz

Date: 22.NOV.2012 12:07:32

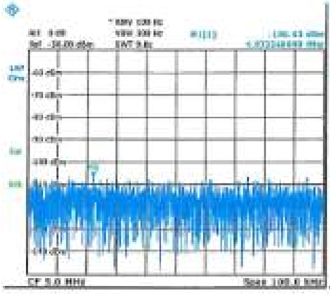
4.3.6. Spurious 10MHz 2

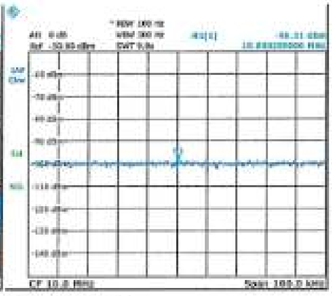


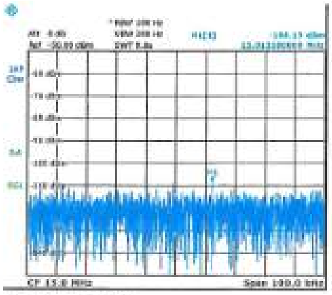
*RBW 100 Hz Marker 1 [T1]
11.33 dBm
Ref 15 dBm *Att 40 dB AQT 32 s 9.960000000 MHz
Delta 2 [T1]
-83.07 dB
1.040000000 MHz

Date: 22.NOV.2012 12:09:46

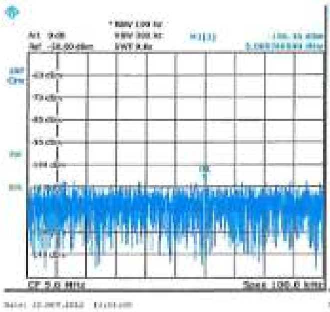
4.3.7. Isolation between 5MHz1 and 10MHz 1

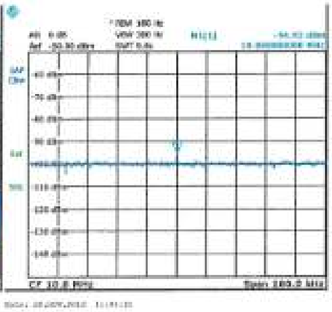


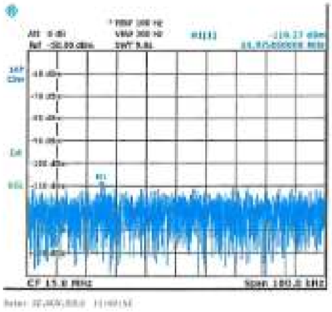




4.3.8. Isolation between 5MHz1 and 10MHz 2

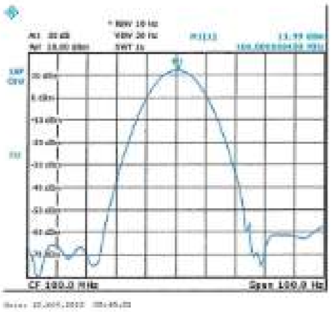






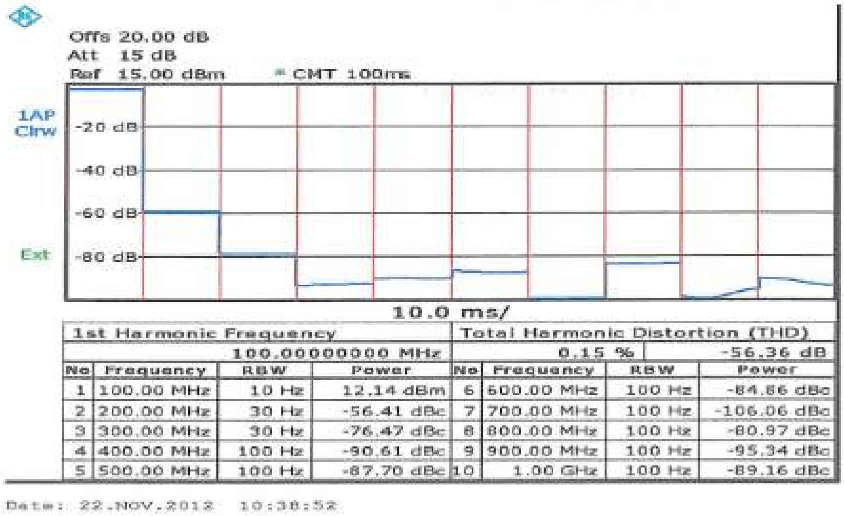
4.4. Outputs signals 100MHz

4.4.1. Output level 100MHz 1



4.4.2. Output level 100MHz2

4.4.3. Harmonics 100MHz 1

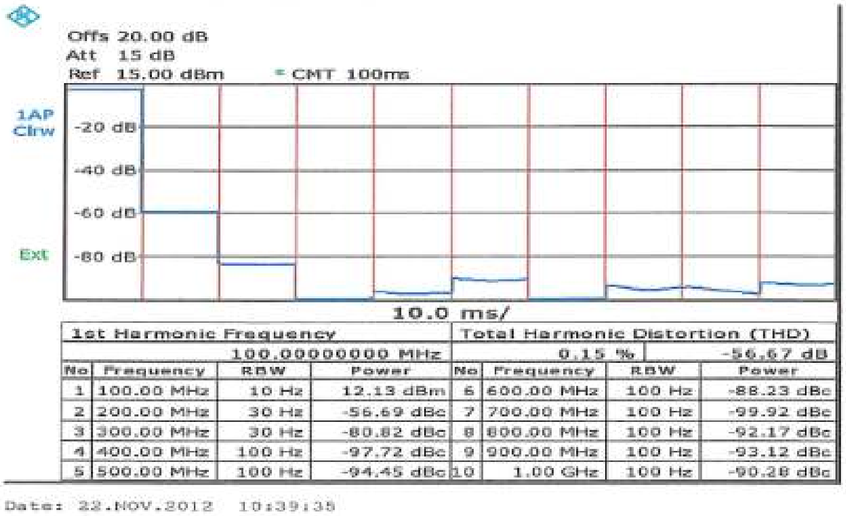


1st Harmonic Frequency: 100.00000000 MHz
Total Harmonic Distortion (THD): 0.15 % -56.36 dB

No	Frequency	RBW	Power	No	Frequency	RBW	Power
1	100.00 MHz	10 Hz	12.14 dBm	6	600.00 MHz	100 Hz	-84.86 dBc
2	200.00 MHz	30 Hz	-56.41 dBc	7	700.00 MHz	100 Hz	-106.06 dBc
3	300.00 MHz	30 Hz	-76.47 dBc	8	800.00 MHz	100 Hz	-80.97 dBc
4	400.00 MHz	100 Hz	-90.61 dBc	9	900.00 MHz	100 Hz	-95.34 dBc
5	500.00 MHz	100 Hz	-87.70 dBc	10	1.00 GHz	100 Hz	-89.16 dBc

Date: 22.NOV.2012 10:38:52

4.4.4. Harmonics 100MHz 2

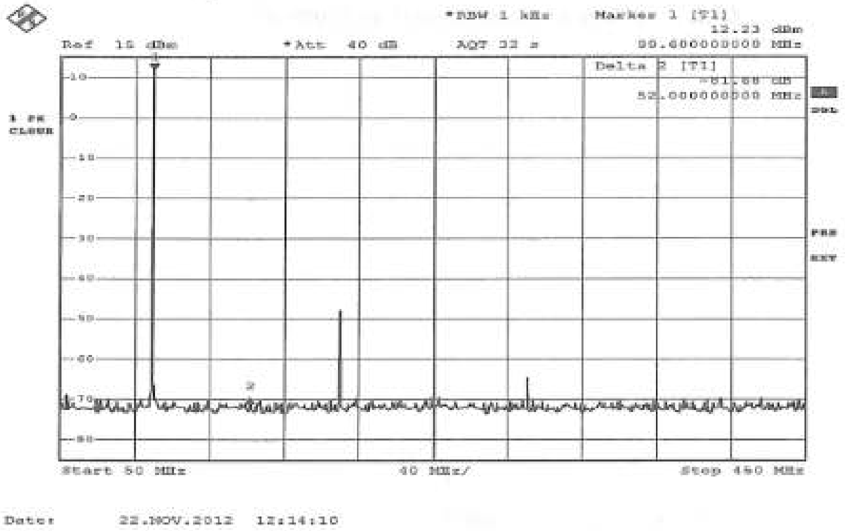


1st Harmonic Frequency: 100.00000000 MHz
Total Harmonic Distortion (THD): 0.15 % -56.67 dB

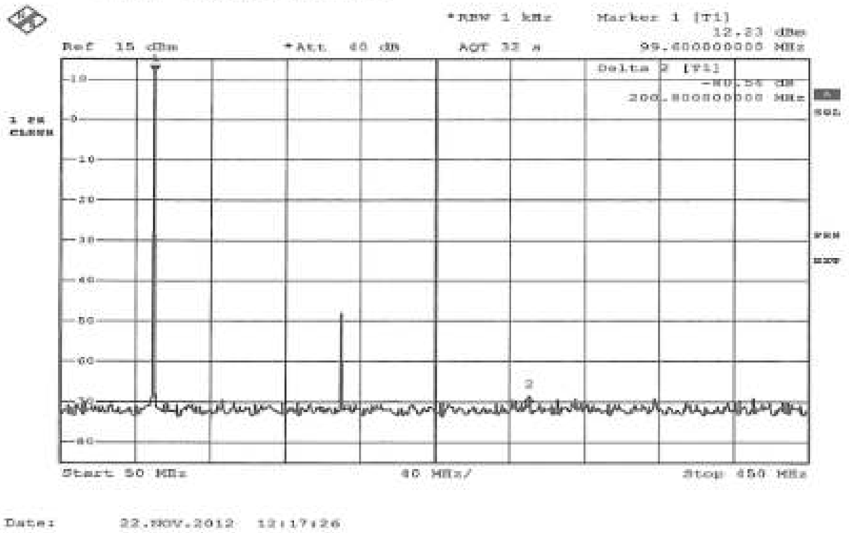
No	Frequency	RBW	Power	No	Frequency	RBW	Power
1	100.00 MHz	10 Hz	12.13 dBm	6	600.00 MHz	100 Hz	-88.23 dBc
2	200.00 MHz	30 Hz	-56.69 dBc	7	700.00 MHz	100 Hz	-99.92 dBc
3	300.00 MHz	30 Hz	-80.82 dBc	8	800.00 MHz	100 Hz	-92.17 dBc
4	400.00 MHz	100 Hz	-97.72 dBc	9	900.00 MHz	100 Hz	-93.12 dBc
5	500.00 MHz	100 Hz	-94.45 dBc	10	1.00 GHz	100 Hz	-90.28 dBc

Date: 22.NOV.2012 10:39:35

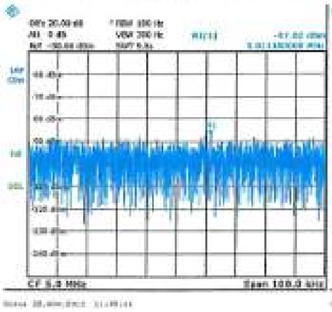
4.4.5. Spurious 100MHz 1

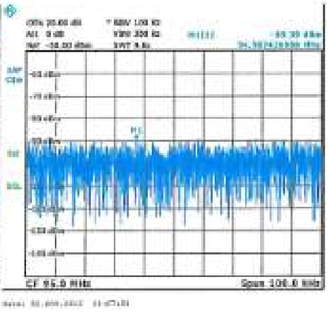


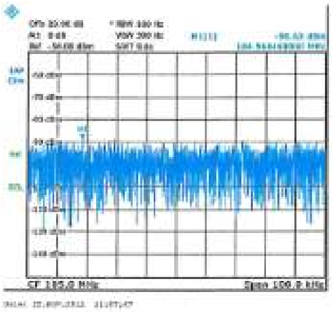
4.4.6. Spurious 100MHz 2



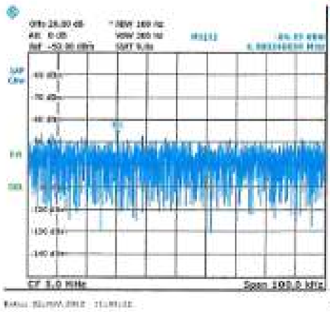
4.4.7. Isolation between 5MHz1 and 100MHz 1

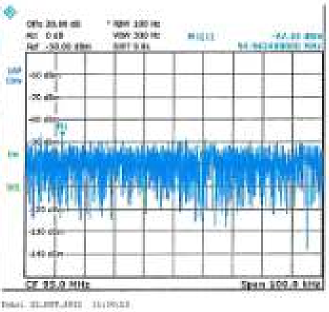


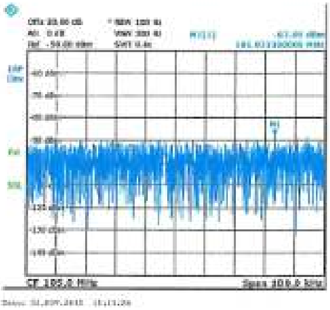




4.4.8. Isolation between 5MHz1 and 100MHz 2







4.5.1PPS clock

Rem: Measured at 50 ohm

iM74 PPS1

Measure	P1:width(C1)	P2:max(C1)	P3:pkpk(C1)	P4:- - -	P5:- - -	P6:- - -
value	99.9794 µs	2.30 V	2.47 V			
mean	99.977442 µs	2.2781 V	2.5098 V			
min	99.9664 µs	2.14 V	2.47 V			
max	99.9898 µs	2.39 V	2.72 V			
sdev	4.122 ns	43.0 mV	72.7 mV			
num	10	10	10			
status	✓	✓	✓			

12/13/2012 3:36:43 PM

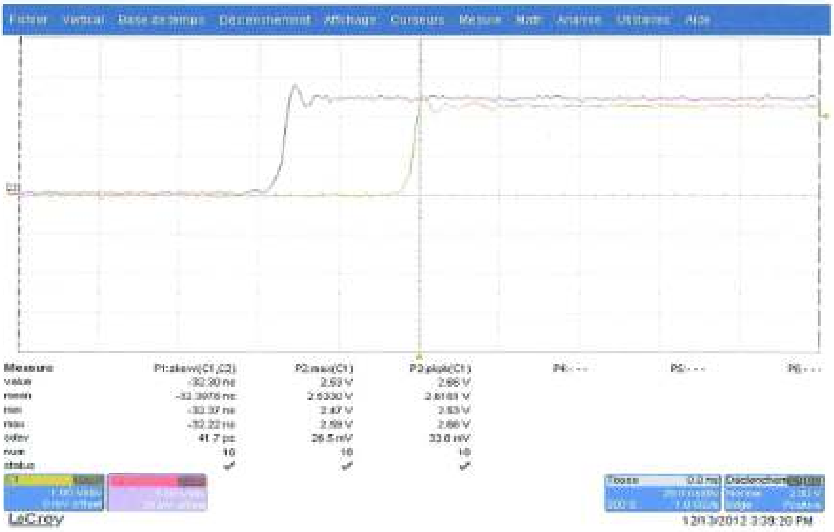
Measure	P1:rise2080(C1)	P2:max(C1)	P3:pkpk(C1)	P4:- - -	P5:- - -	P6:- - -
value	1.997 ns	2.53 V	2.63 V			
mean	2.00151 ns	2.5511 V	2.6420 V			
min	1.880 ns	2.53 V	2.59 V			
max	2.303 ns	2.59 V	2.69 V			
sdev	110.61 ps	24.1 mV	27.8 mV			
num	11	11	11			
status	✓	✓	✓			

12/13/2012 3:37:30 PM

Measure	P1:fall8020(C1)	P2:max(C1)	P3:pkpk(C1)	P4:- - -	P5:- - -	P6:- - -
value	3.166 ns	2.31 V	2.56 V			
mean	3.20471 ns	2.3413 V	2.5817 V			
min	2.893 ns	2.31 V	2.50 V			
max	3.413 ns	2.41 V	2.63 V			
sdev	146.37 ps	32.8 mV	33.7 mV			
num	13	13	13			
status	✓	✓	✓			

Tbase 0.0 ns
20.0 ns/div
400 S 2.0 GS/s
Déclenchement
Normal 2.00 V
Edge Négative

12/13/2012 3:38:26 PM



Measure	P1:skew(C1,C2)	P2:max(C1)	P3:pkpk(C1)	P4:- - -	P5:- - -	P6:- - -
value	-32.30 ns	2.53 V	2.66 V			
mean	-32.3976 ns	2.5330 V	2.6163 V			
min	-32.37 ns	2.47 V	2.53 V			
max	-32.22 ns	2.59 V	2.66 V			
sdev	41.7 ps	26.5 mV	33.8 mV			
num	10	10	10			
status	✓	✓	✓			

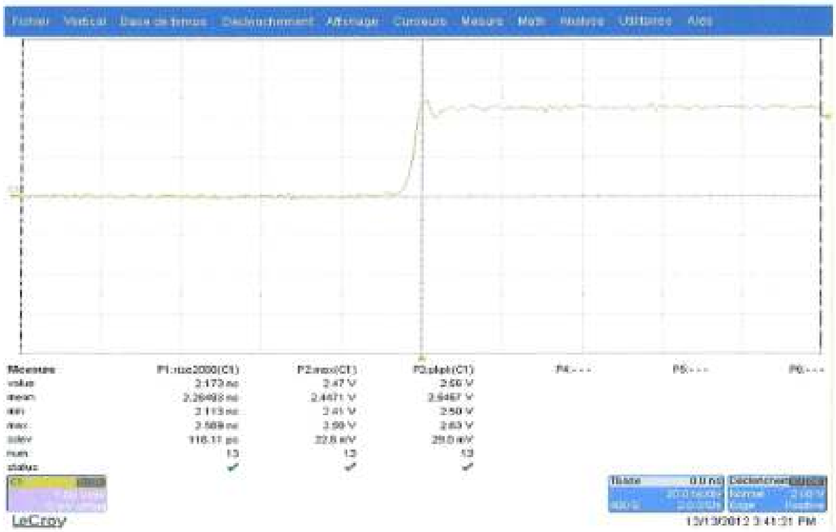
Tbase 0.0 ns
20.0 ns/div
200 S 1.0 GS/s
Déclenchement
Normal 2.00 V
Edge Positive

12/13/2012 3:39:20 PM

iM74 PPS2

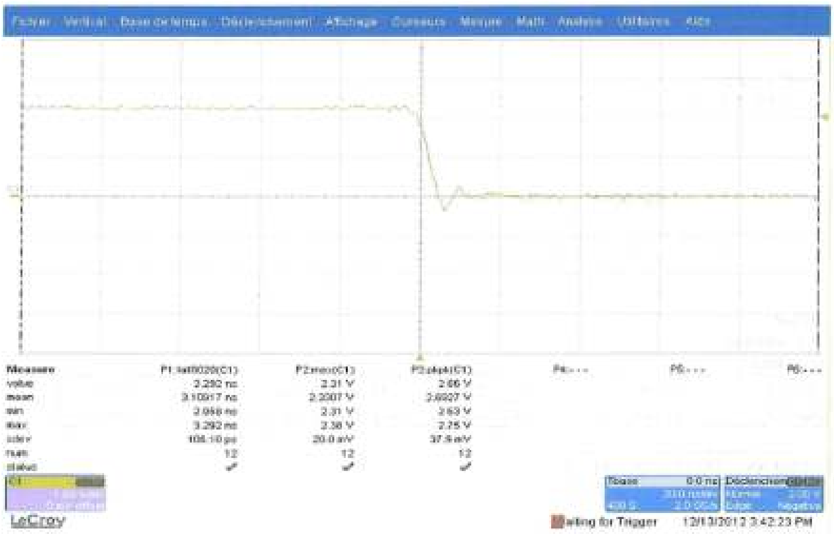
Measure	P1:width(C1)	P2:max(C1)	P3:pkpk(C1)	P4:---	P5:---	P6:---
value	99.9798 µs	2.34 V	2.44 V			
mean	99.976834 µs	2.3583 V	2.5187 V			
min	99.9685 µs	2.34 V	2.44 V			
max	99.9798 µs	2.44 V	2.72 V			
sdev	3.782 ns	25.0 mV	69.7 mV			
num	15	15	15			
status	✓	✓	✓			

12/13/2012 3:40:38 PM



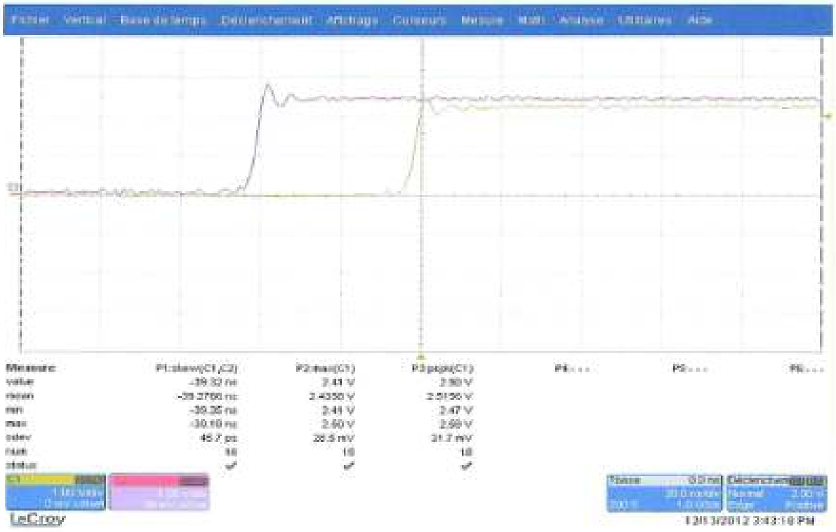
Measure	P1:rise2080(C1)	P2:max(C1)	P3:pkpk(C1)	P4:---	P5:---	P6:---
value	2.173 ns	2.47 V	2.50 V			
mean	2.26493 ns	2.4471 V	2.5467 V			
min	2.113 ns	2.41 V	2.50 V			
max	2.589 ns	2.50 V	2.63 V			
sdev	116.11 ps	22.8 mV	29.0 mV			
num	13	13	13			
status	✓	✓	✓			

12/13/2012 3:41:21 PM



Measure	P1:fall8020(C1)	P2:max(C1)	P3:pkpk(C1)	P4:- - -	P5:- - -	P6:- - -
value	2.292 ns	2.31 V	2.66 V			
mean	3.10917 ns	2.2307 V	2.6927 V			
min	2.958 ns	2.31 V	2.63 V			
max	3.292 ns	2.38 V	2.75 V			
sdev	108.10 ps	20.0 mV	37.5 mV			
num	12	12	12			
status	✓	✓	✓			

Waiting for Trigger 12/13/2012 3:42:23 PM



Measure	P1:skew(C1,C2)	P2:max(C1)	P3:pkpk(C1)	P4:- - -	P5:- - -	P6:- - -
value	-39.32 ns	2.41 V	2.50 V			
mean	-39.2766 ns	2.4350 V	2.5156 V			
min	-39.36 ns	2.41 V	2.47 V			
max	-39.19 ns	2.60 V	2.59 V			
sdev	45.7 ps	28.5 mV	31.7 mV			
num	18	18	18			
status	✓	✓	✓			

12/13/2012 3:43:10 PM

PPS 1 output
Date:13.12.2012

Signal out

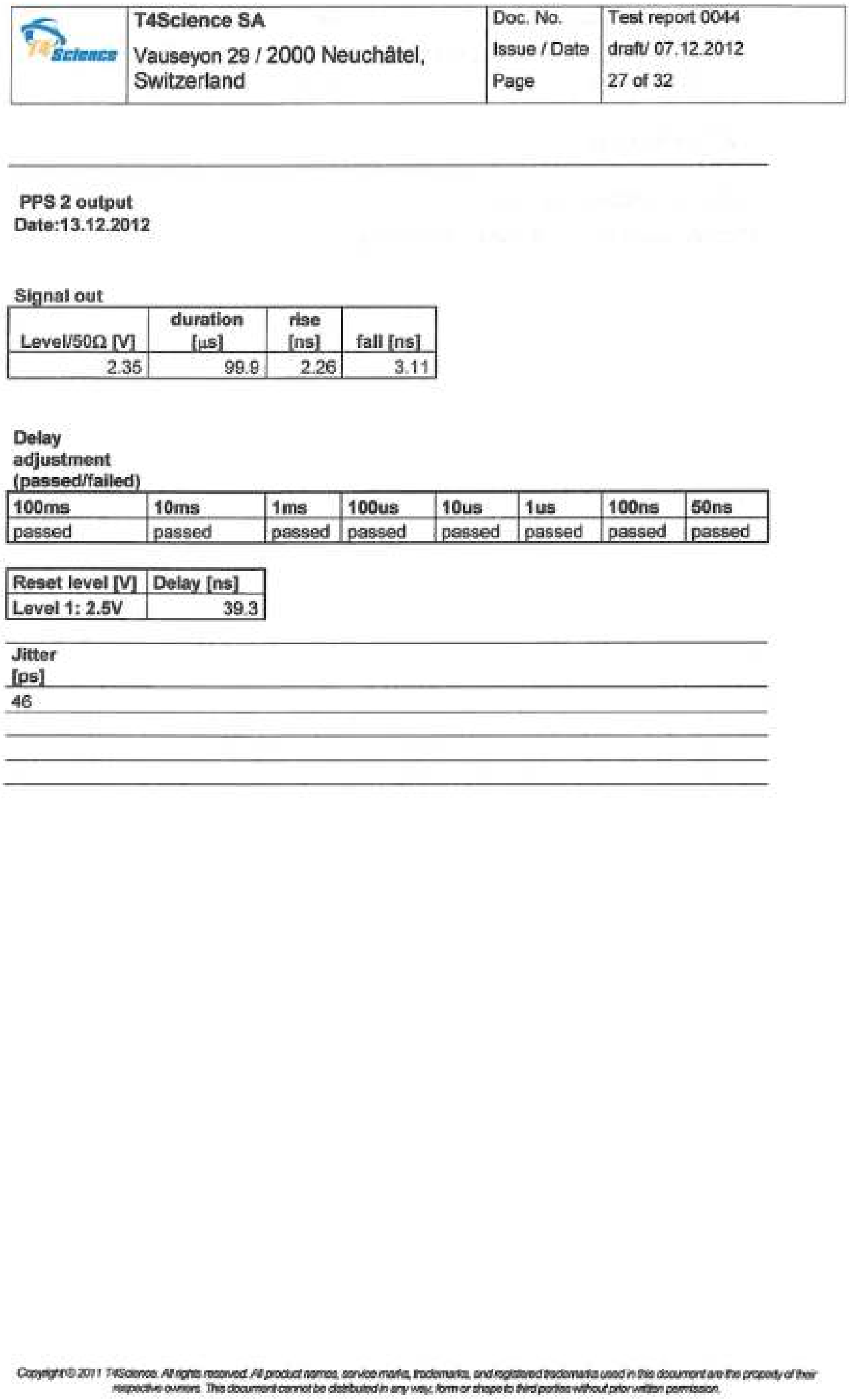
Level/50Ω [V]	**duration** [µs]	**rise** [ns]	fall [ns]
2.37	99.9	2.00	3.20

Delay adjustment (passed/failed)

100ms	**10ms**	**1ms**	**100us**	**10us**	**1us**	**100ns**	**50ns**
passed	passed	passed	passed	passed	passed	passed	passed

Reset level [V]	**Delay [ns]**
Level : 2.5V	32.3

Jitter [ps]
42



PPS 2 output
Date:13.12.2012

Signal out

Level/50Ω [V]	duration [µs]	rise [ns]	fall [ns]
2.35	99.9	2.26	3.11

Delay adjustment (passed/failed)

100ms	10ms	1ms	100us	10us	1us	100ns	50ns
passed	passed	passed	passed	passed	passed	passed	passed

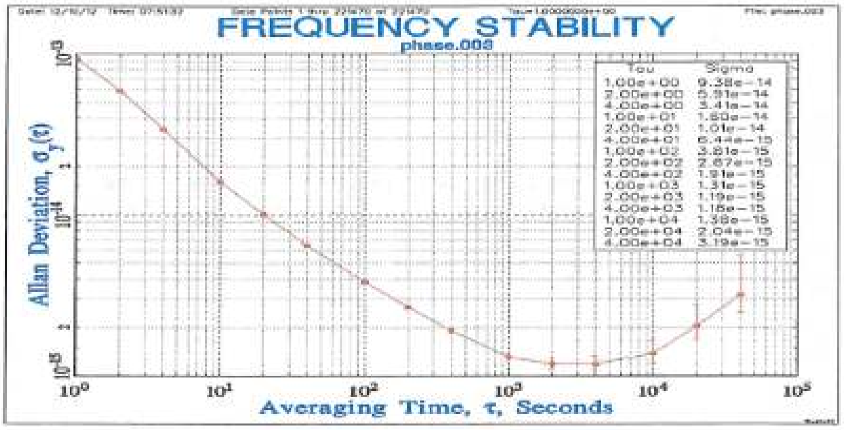
Reset level [V]	Delay [ns]
Level 1: 2.5V	39.3

Jitter [ps]
46

4.6. Stability test

4.6.1. Allan deviation

Allan Variance raw data versus iMaser 78

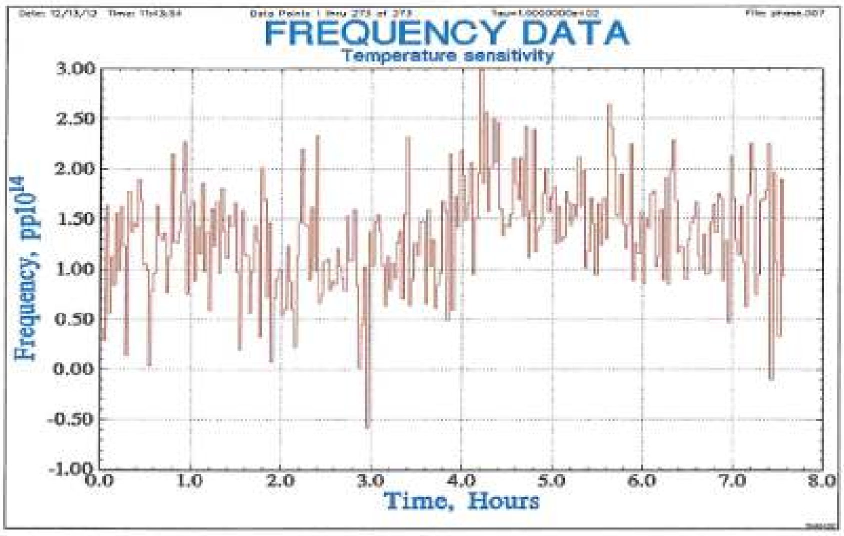


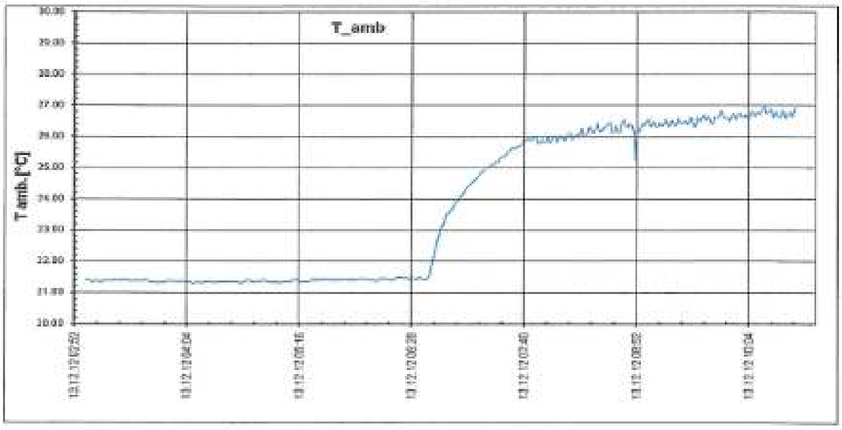
Tau	Sigma
1.00e+00	9.38e−14
2.00e+00	5.91e−14
4.00e+00	3.41e−14
1.00e+01	1.60e−14
2.00e+01	1.01e−14
4.00e+01	6.44e−15
1.00e+02	3.81e−15
2.00e+02	2.67e−15
4.00e+02	1.91e−15
1.00e+03	1.31e−15
2.00e+03	1.19e−15
4.00e+03	1.18e−15
1.00e+04	1.38e−15
2.00e+04	2.04e−15
4.00e+04	3.19e−15

4.6.2. Temperature sensitivity

iM68 vs iM52

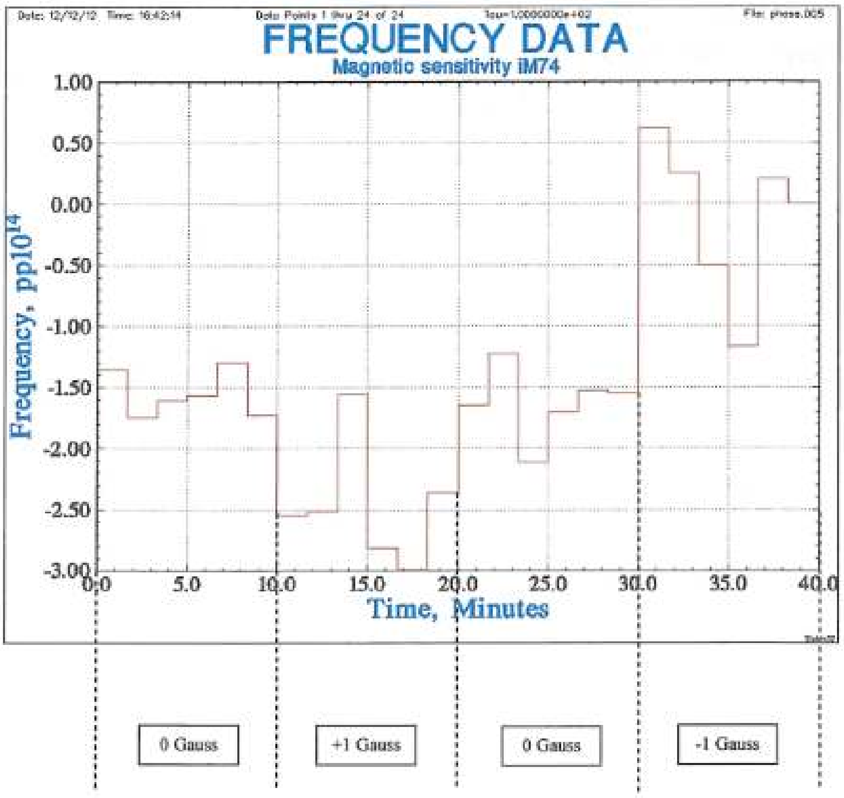
Temp sensitivity: 3 e-15 / °C





4.6.3. Magnetic test record At Spin Exchange

Avg 100 in Z field



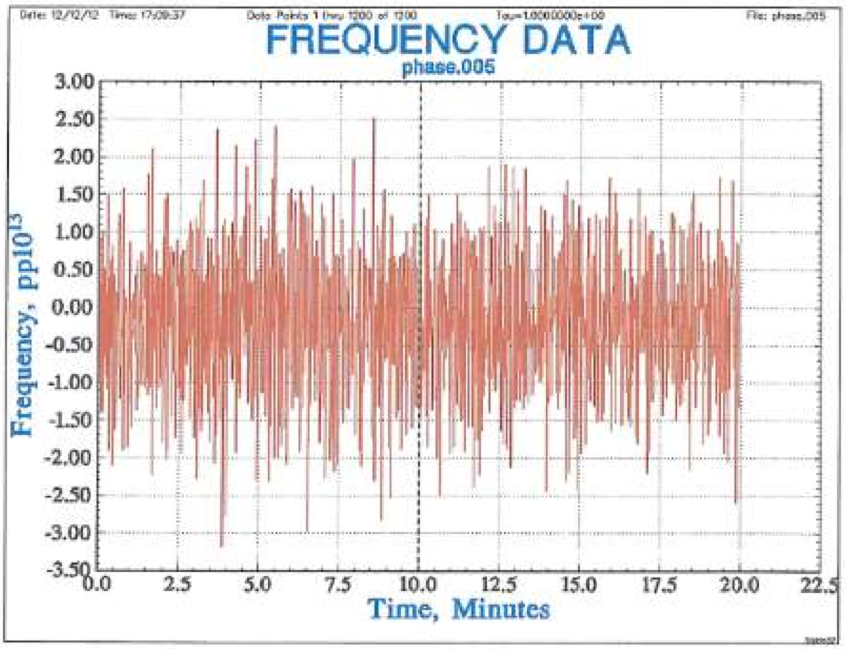
Result: (-3e-14 - 0.6e-14) / 2 G = 1.8 e-14 / Gauss

Note: there is no measurable effect of the field in other direction (X or Y).

4.6.4. AC Power Break

AC power break iM74

Note that the dotted line indicates the moment of AC removal.



5. Conclusion

All tests proposed in Test plan have been made.

All results are within specifications.

The unit is ready for customer acceptance tests and validation.

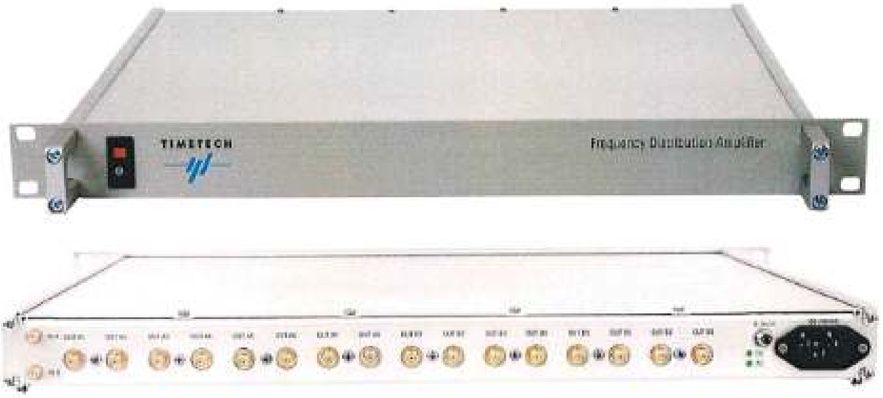
Allegato 3

TIMETECH

Frequency Distribution Amplifier

High Performance
5 to 100 MHz, Dual Chain: 1 Input to 8 Outputs each

Part No: 10274



Key features:

- Compact design (1HU), rack mountable
- Low phase noise
- Very high output and reverse isolation
- Excellent input and output match to 50 Ω
- Excellent for high performance frequency references
- Useable 100 kHz to 200 MHz
- AC and DC power supply inputs, automatic switch-over

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Fax: ++49 711 67808-99
e-mail: info@TimeTech.de
web: www.TimeTech.de

Frequency Distribution Amplifier

Part No: 10274

High Performance, 5 to 100 MHz, Dual Chain: 1 Input to 8 Outputs each

TIMETECH

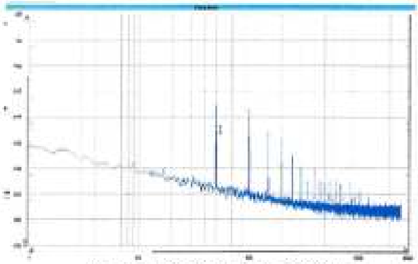
The Frequency Distribution Amplifier is a one height unit rack mountable unit. The unit allows a cost and space efficient way to distribute reference frequencies throughout a system without any loss or degradation. The standard product gain is 0 dB. Different gain is available on customer request.

The Distribution Amplifier is optimised for very low phase noise, very good input and output match to 50 Ω and for excellent isolation – this is for output to output and output to input.

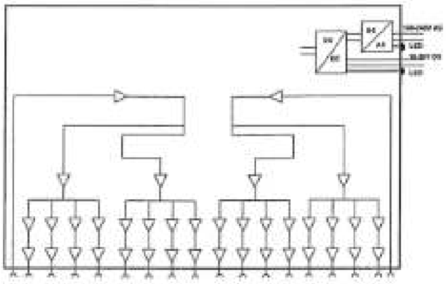
The Distribution Amplifier provides very high stability of signal delay so that it can be used with high precision frequency sources such as caesium clocks or masers.

The Distribution Amplifier is designed to minimise phase noise and shows the following performance, measured under laboratory environment, temperature +18 .. +24°C, controlled to 1K pp with maximum slopes of 0.5 K/h:

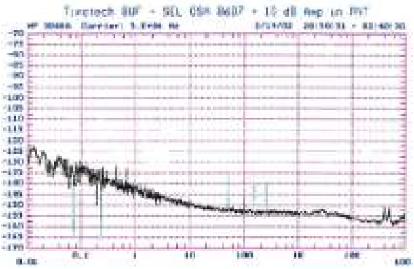
Freq. / Offset [Hz]	Phase Noise [dBc]		
	5 MHz	10 MHz	100 MHz
0.1 Hz	-132		
1 Hz	-142	-141	-131
10 Hz	-149	-148	-140
100 Hz	-152	-152	-150
1000 Hz	-153	-153	-153
10000 Hz	-153	-153	-153



Phase noise at 100 MHz, +8 dBm



Block diagram of the Frequency Distribution Amplifier



Phase noise at 5 MHz, +13 dBm, 0.01 Hz to 100 kHz

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TIMETECH

Frequency Distribution Amplifier

Part No: 10274

High Performance, 5 to 100 MHz, Dual Chain: 1 Input to 8 Outputs each

Specification

Signal Inputs	
Number of inputs	1 per chain (total 2 inputs)
Frequency	5 to 100 MHz, sine wave, useable from 100 kHz to 200 MHz
Input impedance	50 Ω, nominal
Input level working	+6 to +17 dBm (+14 dBm @ 100 MHz, 13 dBm @ 200 MHz)
Input level nominal	+13 dBm
Input return loss	> 40 dB (43 dB typ. @ 5, 10 and 100 MHz, > 30 dB @ 200 MHz)
Connectors	SMA, BNC option via adaptors
Signal Outputs	
Number of outputs	8 per chain, two chains (total 16 outputs)
Gain	0 dB (+0.15/-0.1 dB, 1 – 100 MHz, +0.15 to -0.5dB @ 200 MHz)
Gain variation	< 0.1 dB, output vs. output and input A vs. input B
Output impedance	50 Ω, nominal
Output return loss	> 40 dB (> 42 dB typ., 1 – 100 MHz)
Connectors	SMA, BNC option via adaptors
Noise figure	< 22.0 dB, (21 dB typ., 1 – 100 MHz)

Group delay absolute, 1 – 100 MHz	4.8 ns ±1 ns
Group delay flatness, 1 – 100 MHz	< 0.1 ns pp
Group delay variation, channel vs. channel	< 0.1 ns
Group delay variation versus temperature	< 6 ps / K

		5 MHz	10 MHz	100 MHz	200 MHz
Gain compression: 0.1 dB at		Pout = + 17 dBm	+ 17 dBm	+ 14 dBm	+ 11 dBm
Gain compression: 1 dB at		Pout = + 18 dBm	+ 18 dBm	+ 15 dBm	+ 13 dBm
Reverse Isolation [dB]		> 140 (150 typ.)	> 140 (150 typ.)	> 140	> 120
Input / Input Isolation [dB]		> 140	> 140	> 110 (120 typ.)	> 100
ChA / ChB Isolation [dB]		> 130	> 130	> 100	> 90
Output / Output Isolation [dB]		> 120 (128 typ.)	> 120 (128 typ.)	> 110 (118 typ.)	> 105
Harmonics [dBc]	+10 dBm	-76 -76 -80	-70 -57 -65	-44 -46 -60	
(1st, 2nd, 3rd)	+13 dBm	-73 -69 -82	-65 -55 -64	-42 -40 -55	

Electrical interface		
Power Consumption	AC: < 15 W	Priority on AC supply input
(all outputs loaded)	DC: < 10 W, Stand-By: < 0.8 W	DC is used as back-up supply.
Supply voltage AC	95 to 265 V AC, 47 to 65 Hz	LED indicating AC voltage
Supply voltage DC	18 to 36 V DC, DC isolated	LED indicating DC voltage
	DC connector included, IEC 61076-2-101 M8	
	(+) brown (1) & white (2), (-) blue (3) & black (4), polarity reversible	

Mechanical	
Outline	19 inch, 1 height unit (448.8 mm * 44 mm) depth 448 mm
Weight	1.5 kg
Environmental	
Transportation and Storage	
Temperature.	-20°C to +75°C
Humidity	10% to 90% (non condensing)
Altitude	< 20 000 m
Shock	max. 10g acceleration for 11 ms
Vibration	max. 0.15 mm at 5 to 8 Hz, max. 1g acceleration at 8 to 500 Hz
Operation	
Temperature	-10°C to +50°C
Humidity	20% to 90% (non condensing)
Altitude	< 3 000 m
Option	BNC adapters for all connectors

21 Mar 2006

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Allegato 4

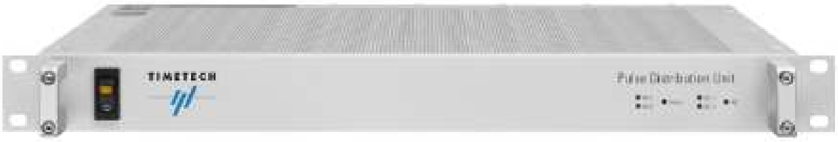
Pulse Distribution Unit

Low Profile

1PPS, to 200 MHz, 2 in - 16 out, BNC

Issue 1

Part No: 10545



Pulse Distribution Unit

Part No: 10545
1PPS, to 200 MHz, 2 in - 16 out, BNC

TIMETECH

Key features:

- 1pps time signal distribution
- Long distance transmission of pulse signals (1pps) with high delay stability and low jitter
- Compact design (1HU), rack mount
- High speed input comparator for signal restoration
- Short rise and fall times (t_r, t_f < 500 ps, 400 ps typ)
- Added jitter: < 2 ps
- Output to output skew: < 20 ps (10 ps typ)
- Instrument absolute delay: 6.5 ns nominal
- Temperature coefficient: 6 ps/K
- Matched to 50 Ohm
- BNC connectors
- DC coupled input for positive pulses, configurable trigger level
- AC coupled input for square wave input and for conversion of sine to square wave
- Usable for digital pulse distribution from below 1 PPS to 200 MHz
- AC and 2 x DC power supply inputs, automatic switch-over

Description

The Pulse Distribution Unit is a 1HU mount unit with very short rise and fall times, and provides 1 PPS (one pulse per second) pulses to 16 outputs. Together with a low temperature coefficient and very small channel-to-channel delay variation, this makes the unit ideal for high stability pulse distribution applications. Its fast input comparator accepts a wide range of input signals. Its trigger level can be set by rotary switch. The outputs are TTL signals when unloaded and 2.5 Vpp when loaded with 50 Ohm.

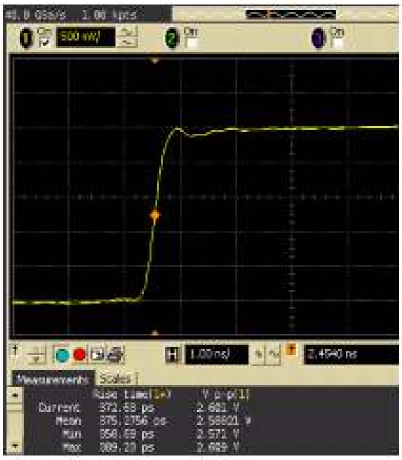
The unit is designed to use the rising edge as the significant pulse reference. A typical 1 PPS signal has a short pulse width only, but pulses of any duty cycle can be transmitted. The presence of input pulses is shown by an input LED indicator. A red ALRM LED shows an output failure or no signal present.

There are two selectable input connectors, both feature a high-speed input comparator:

- Input A is AC coupled for converting bipolar pulse or sine wave inputs into positive pulses. The trigger level is fixed at 0 V. Sine input will be converted to square wave of 50% duty cycle.
- Input B is DC coupled for distributing of positive pulses. The trigger level is configurable. It can be used to convert sinusoidal signals to square wave, with trigger set to 0V.

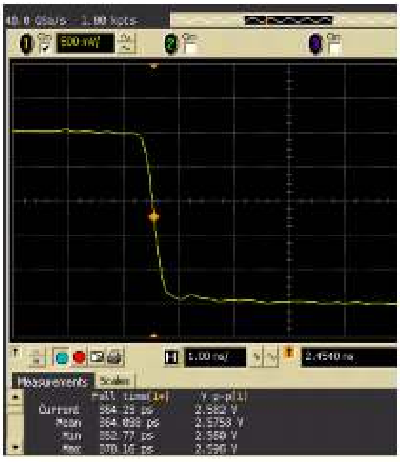
Typical Waveforms

The signal outputs exhibit rise and fall times below 400 ps, shown below.



```
          Rise time(1↗)     V p-p(1)
Current   372.68 ps         2.601 V
   Mean   375.2756 ps       2.58821 V
    Min   358.69 ps         2.571 V
    Max   389.23 ps         2.609 V
```

Fig 1a: Example rise time of 375 ps



```
          Fall time(1↘)     V p-p(1)
Current   364.23 ps         2.582 V
   Mean   364.098 ps        2.5759 V
    Min   352.77 ps         2.560 V
    Max   378.16 ps         2.590 V
```

Fig 1b: Example fall time of 364 ps

- Test cable: 0.8 m ECOFLEX 10 (must have good RF characteristics)
- Scope bandwidth limited to 3 GHz
- **Long distance transmission example**

The transmission of a pulse signal over a distance of 310 m of FSJ1 cable using two units of 10545 is demonstrated.
A 310 m long high-stability co-axial cable (FSJ1) was connected in between two units as shown in Figure 2a. Performance was measured at the output of unit 2.

Setup:

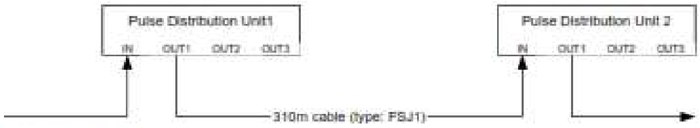


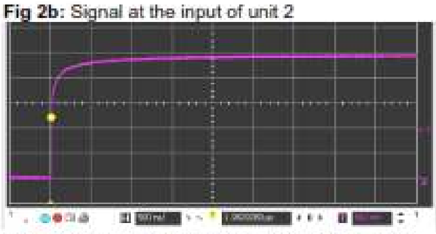
Fig 2a: Test setup

- Input to unit1: 1PPS signal (20 µs width) from a 1 PPS generator (not shown)
- Trigger level of unit 2 = 0.6V
- All loads 50 Ω

Results:

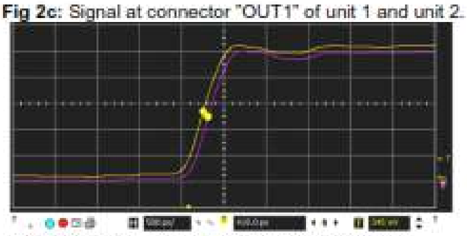
1. Pulse shape

Fig 2b: Signal at the input of unit 2



Horizontal scale: 500 ns/div (rise time 160 ns)
Vertical scale: 500 mV/div

Fig 2c: Signal at connector "OUT1" of unit 1 and unit 2.



Horizontal scal: 150 ps/div (rise time 400 ps)
Vertical scale: 500 mV/div

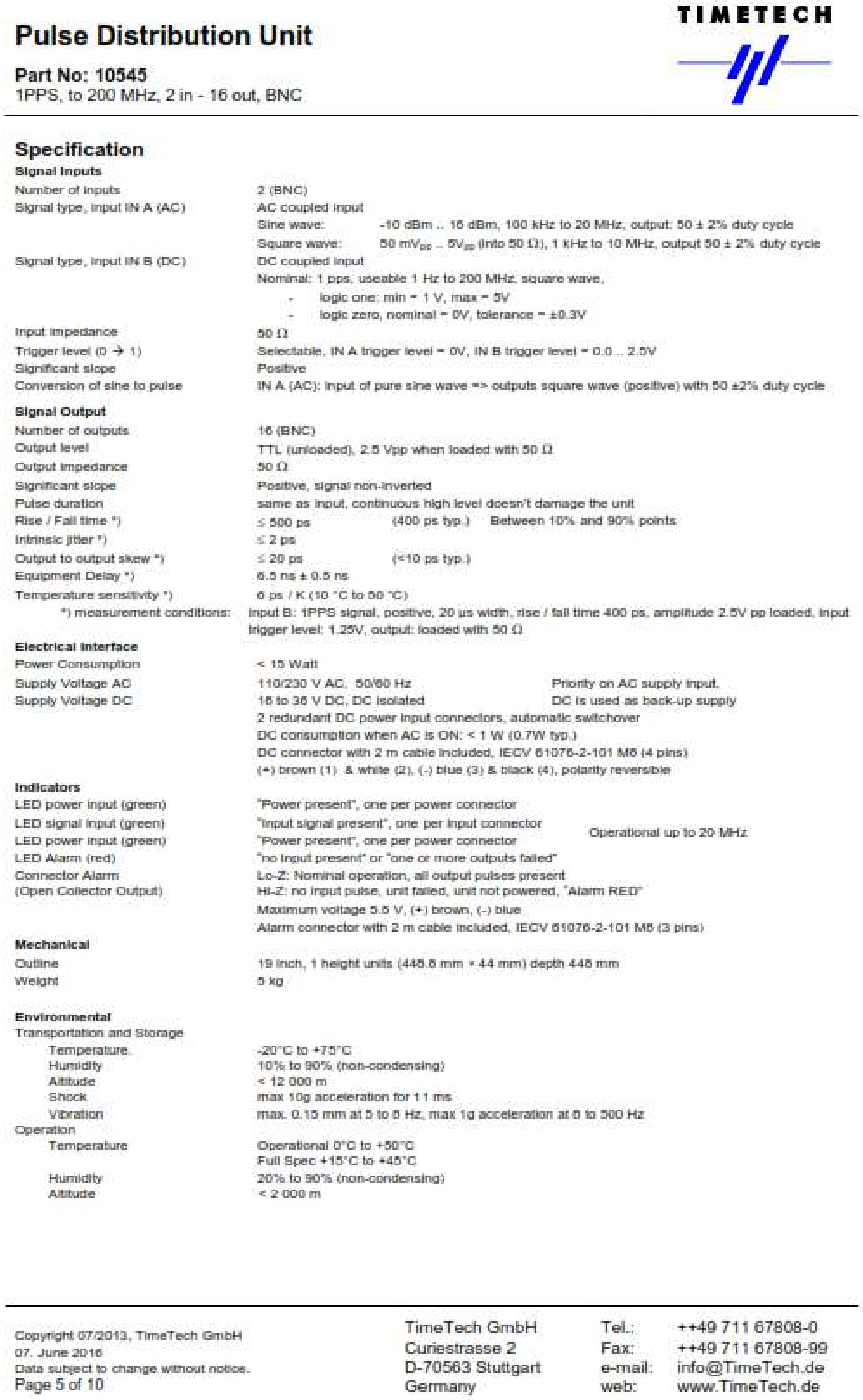
2. Pulse jitter

Jitter with 310 m cable (FSJ1): <10 ps

3. Temperature coefficient

Temperature coefficient of 310 m cable (FSJ1) alone:	10 ps/K
Temperature coefficient of 2 units of 10545	12 ps/K
Total temperature coefficient over 310 m transmission:	<22 ps/K (incl. units)

Note:
Even better results can be expected with cables having less high frequency losses with foam dielectric, like Ecoflex 10, Ecoflex 15 or LDF4-50.



Pulse Distribution Unit

TIMETECH

Part No: 10545
1PPS, to 200 MHz, 2 in - 16 out, BNC

Specification

Signal Inputs		
Number of inputs	2 (BNC)	
Signal type, input IN A (AC)	AC coupled input	
	Sine wave:	-10 dBm .. 16 dBm, 100 kHz to 20 MHz, output: 50 ± 2% duty cycle
	Square wave:	50 mV$_{pp}$ .. 5V$_{pp}$ (into 50 Ω), 1 kHz to 10 MHz, output 50 ± 2% duty cycle
Signal type, input IN B (DC)	DC coupled input Nominal: 1 pps, useable 1 Hz to 200 MHz, square wave, - logic one: min = 1 V, max = 5V - logic zero, nominal = 0V, tolerance = ±0.3V	
Input impedance	50 Ω	
Trigger level (0 → 1)	Selectable, IN A trigger level = 0V, IN B trigger level = 0.0 .. 2.5V	
Significant slope	Positive	
Conversion of sine to pulse	IN A (AC): input of pure sine wave => outputs square wave (positive) with 50 ±2% duty cycle	
Signal Output		
Number of outputs	16 (BNC)	
Output level	TTL (unloaded), 2.5 Vpp when loaded with 50 Ω	
Output impedance	50 Ω	
Significant slope	Positive, signal non-inverted	
Pulse duration	same as input, continuous high level doesn't damage the unit	
Rise / Fall time *)	≤ 500 ps	(400 ps typ.) Between 10% and 90% points
Intrinsic jitter *)	≤ 2 ps	
Output to output skew *)	≤ 20 ps	(<10 ps typ.)
Equipment Delay *)	6.5 ns ± 0.5 ns	
Temperature sensitivity *)	6 ps / K (10 °C to 50 °C)	
*) measurement conditions:	Input B: 1PPS signal, positive, 20 µs width, rise / fall time 400 ps, amplitude 2.5V pp loaded, input trigger level: 1.25V, output: loaded with 50 Ω	
Electrical Interface		
Power Consumption	< 15 Watt	
Supply Voltage AC	110/230 V AC, 50/60 Hz	Priority on AC supply input.
Supply Voltage DC	18 to 36 V DC, DC isolated	DC is used as back-up supply
	2 redundant DC power input connectors, automatic switchover DC consumption when AC is ON: < 1 W (0.7W typ.) DC connector with 2 m cable included, IECV 61076-2-101 M8 (4 pins) (+) brown (1) & white (2), (-) blue (3) & black (4), polarity reversible	
Indicators		
LED power input (green)	"Power present", one per power connector	
LED signal input (green)	"Input signal present", one per input connector	Operational up to 20 MHz
LED power input (green)	"Power present", one per power connector	
LED Alarm (red)	"no input present" or "one or more outputs failed"	
Connector Alarm (Open Collector Output)	Lo-Z: Nominal operation, all output pulses present Hi-Z: no input pulse, unit failed, unit not powered, "Alarm RED" Maximum voltage 5.5 V, (+) brown, (-) blue Alarm connector with 2 m cable included, IECV 61076-2-101 M8 (3 pins)	
Mechanical		
Outline	19 inch, 1 height units (448.8 mm × 44 mm) depth 448 mm	
Weight	5 kg	
Environmental		
Transportation and Storage		
Temperature	-20°C to +75°C	
Humidity	10% to 90% (non-condensing)	
Altitude	< 12 000 m	
Shock	max 10g acceleration for 11 ms	
Vibration	max. 0.15 mm at 5 to 8 Hz, max 1g acceleration at 8 to 500 Hz	
Operation		
Temperature	Operational 0°C to +50°C Full Spec +15°C to +45°C	
Humidity	20% to 90% (non-condensing)	
Altitude	< 2 000 m	

07. June 2016
Data subject to change without notice.
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Typical characteristics of Input A, (AC)

Input 10 MHz, 13 dBm sine, converted to 10 MHz square wave. Phase noise is shown in **Fig 3a.** .

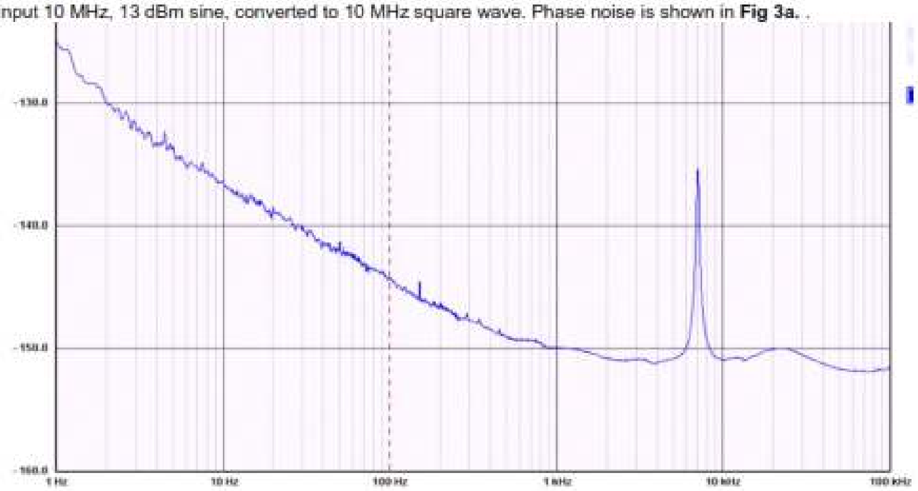


Fig 3a: Phase noise of 10 MHz square wave output, input 10 MHz sine input 13 dBm to input A.

Input 5 MHz, 13 dBm sine, converted to 5 MHz square wave. Phase noise is shown in **Fig 3b.**

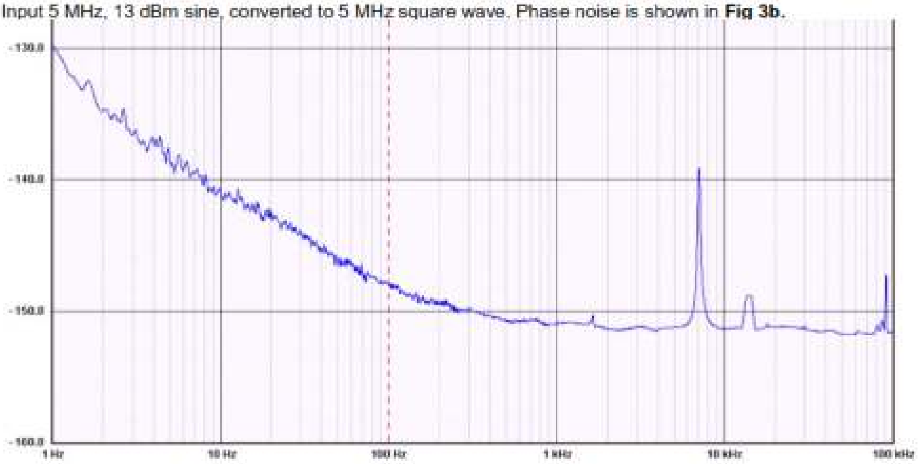


Fig 3b: Phase noise of 5 MHz square wave output, input 5 MHz sine input 13 dBm to input A.

Typical characteristics of Input A, (AC), continued

Input A: Sine input, Output Jitter [ns] (rising edge)			
Frequency \ Input Level	**10 dBm**	**0 dBm**	**-10 dBm**
100 MHz	0,071	0,008	0,015
20 MHz	0,057	0,004	0,010
10 MHz	0,057	0,005	0,011
1 MHz	0,009	0,025	0,064
100 kHz	0,067	0,219	0,636
10 kHz	1,202	3,536	9,192
1 kHz	21,213	49,497	Not triggered

Table 3a: Output jitter [ns], sinusoidal signal to input A

Input A: Square wave input, Output Jitter [ns] (rising edge)			
Frequency \ Input Level	**5 Vpp**	**1 Vpp**	**50 mVpp**
50 MHz	0,002	0,004	0,024
20 MHz	0,002	0,004	0,025
10 MHz	0,001	0,004	0,034
1 MHz	0,001	0,004	0,023
100 kHz	0,002	0,004	0,023
10 kHz	0,002	0,004	0,021
1 kHz	0,002	0,004	0,020
500 Hz	0,002	0,004	Not triggered
100 Hz	0,003	0,005	Not triggered
90 Hz	Not triggered	Not triggered	Not triggered

Table 3b: Output jitter [ns], square wave signal to input A

Typical characteristics of Input B, (DC)

Conversion of sine to square coupled to input B, Input 100MHz, 7 dBm sine. Phase noise is shown in Fig 4a.

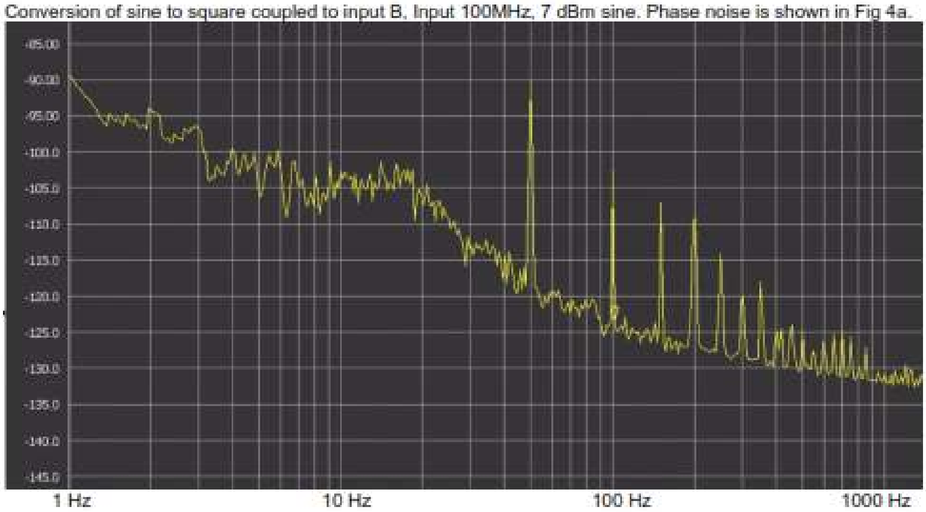


Fig 4a: Phase noise of 100 MHz square wave output, input 100 MHz sine, 7 dBm to input B, trigger 0V

Conversion of sine to square coupled to input B, Input 10MHz, 13 dBm sine. Phase noise is shown in Fig 4b.

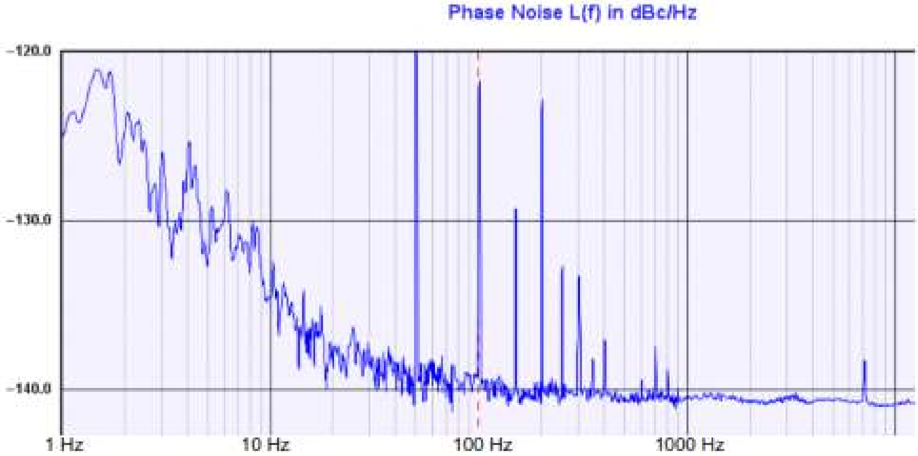


Fig 4b: Phase noise of 10 MHz square wave output, input 10 MHz sine, 13 dBm to input B, trigger 0V

Typical characteristics of Input B, (DC), continued

Conversion of sine to square coupled to input B, Input 5MHz, 13 dBm sine. Phase noise is shown in Fig 4c

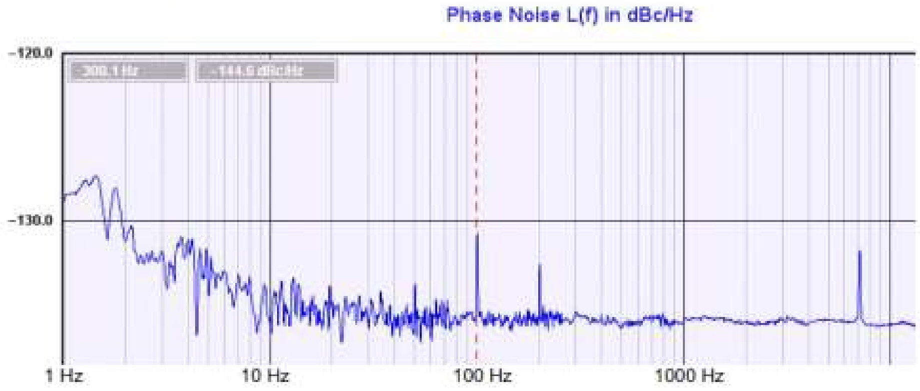


Fig 4c: Phase noise of 5 MHz square wave output, input 5 MHz sine, 13 dBm to input B, trigger 0V

As the IN B is DC coupled it works with arbitrary low frequency. Triggering is tested down to 1 mHz with an input signal amplitude of –10 dBm. The trigger works perfect with such low frequency and low signal level. The output jitter measured is in the order of

- 1E-4 x (signal period) at 10 dBm sine signal input level
- 1E-3 x (signal period) at -10 dBm sine signal input level

Typical results are shown in Figure 4d

Input B: Sinusoidal input, Output Jitter [ns] (rising edge)				
Frequency \ Input Level	**10 dBm**	**0 dBm**	**-10 dBm**	**Trigger**
10 MHz	0,01	0,04	0,11	OK
1 MHz	0,11	0,30	0,71	OK
100 kHz	0,70	2,12	6,00	OK
10 kHz	6,00	18,00	53,00	OK
1 kHz	46,00	142,00	460,00	OK
100 Hz	475,00	1200,00	4243,00	OK
10 Hz				OK
1 Hz				OK
100 mHz			4245000,00	OK
10 mHz				OK
1 mHz				OK

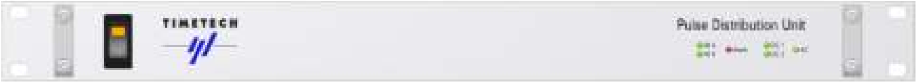
Fig 4d: Output jitter using input B and sinusoidal input signal. Trigger level 0V. Input Signal is DC coupled.

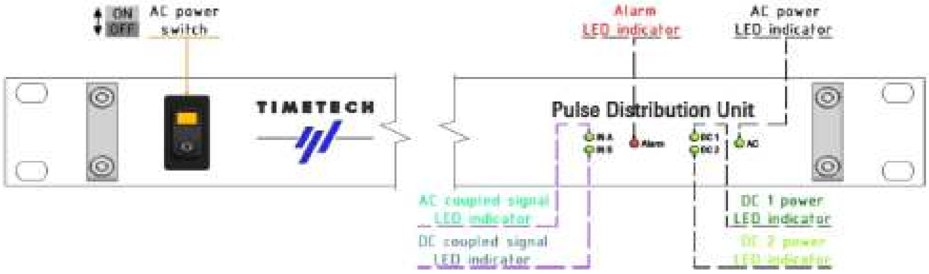
Pulse Distribution Unit

Part No: 10545
1PPS, to 200 MHz, 2 in - 16 out, BNC

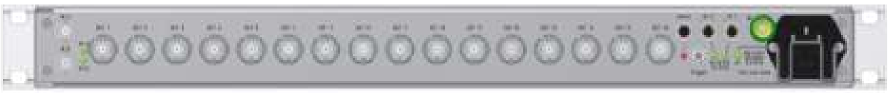
Unit Outline

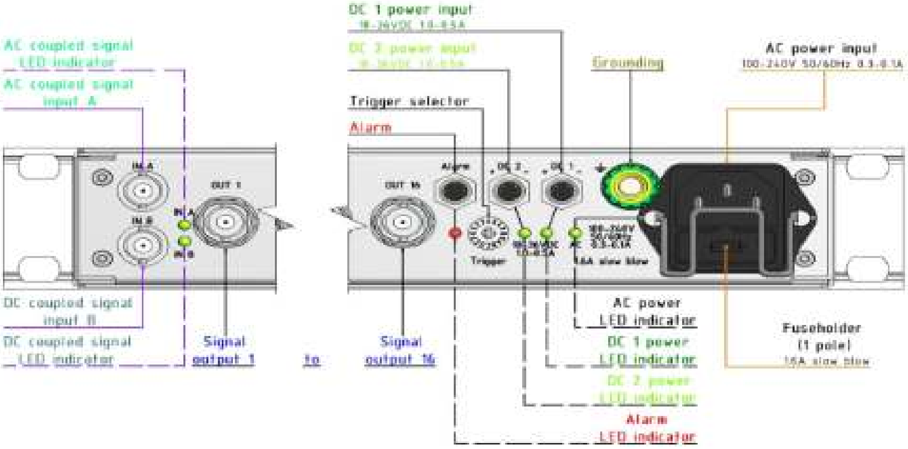
Front View



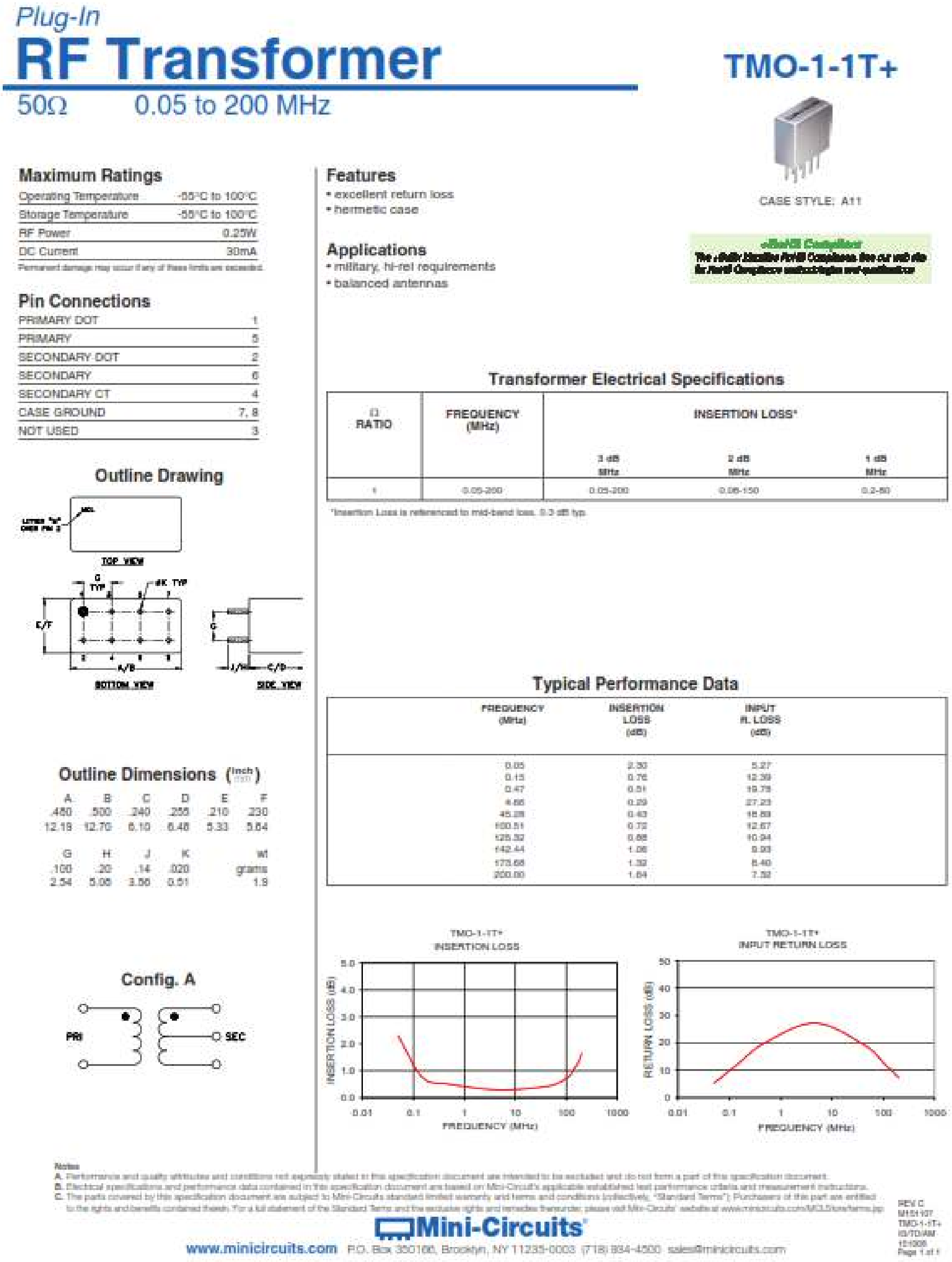


Rear View





Allegato 5



Plug-In

RF Transformer

50Ω 0.05 to 200 MHz

TMO-1-1T+

CASE STYLE: A11

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Maximum Ratings

Operating Temperature	-55°C to 100°C
Storage Temperature	-55°C to 100°C
RF Power	0.25W
DC Current	30mA

Permanent damage may occur if any of these limits are exceeded.

Pin Connections

PRIMARY DOT	1
PRIMARY	5
SECONDARY DOT	2
SECONDARY	6
SECONDARY CT	4
CASE GROUND	7, 8
NOT USED	3

Outline Drawing

Outline Dimensions (inch / mm)

A	B	C	D	E	F
.480	.500	.240	.255	.210	.230
12.19	12.70	6.10	6.48	5.33	5.84

G	H	J	K		wt
.100	.20	.14	.020		grams
2.54	5.08	3.56	0.51		1.9

Config. A

Features

- excellent return loss
- hermetic case

Applications

- military, hi-rel requirements
- balanced antennas

Transformer Electrical Specifications

Ω RATIO	FREQUENCY (MHz)	INSERTION LOSS*		
		3 dB MHz	2 dB MHz	1 dB MHz
1	0.05-200	0.05-200	0.08-150	0.2-80

*Insertion Loss is referenced to mid-band loss, 0.3 dB typ.

Typical Performance Data

FREQUENCY (MHz)	INSERTION LOSS (dB)	INPUT R. LOSS (dB)
0.05	2.30	5.27
0.15	0.76	12.39
0.47	0.51	19.79
4.66	0.29	27.23
45.28	0.43	18.89
100.51	0.72	12.67
125.32	0.88	10.94
142.44	1.06	9.93
173.68	1.32	8.40
200.00	1.64	7.32

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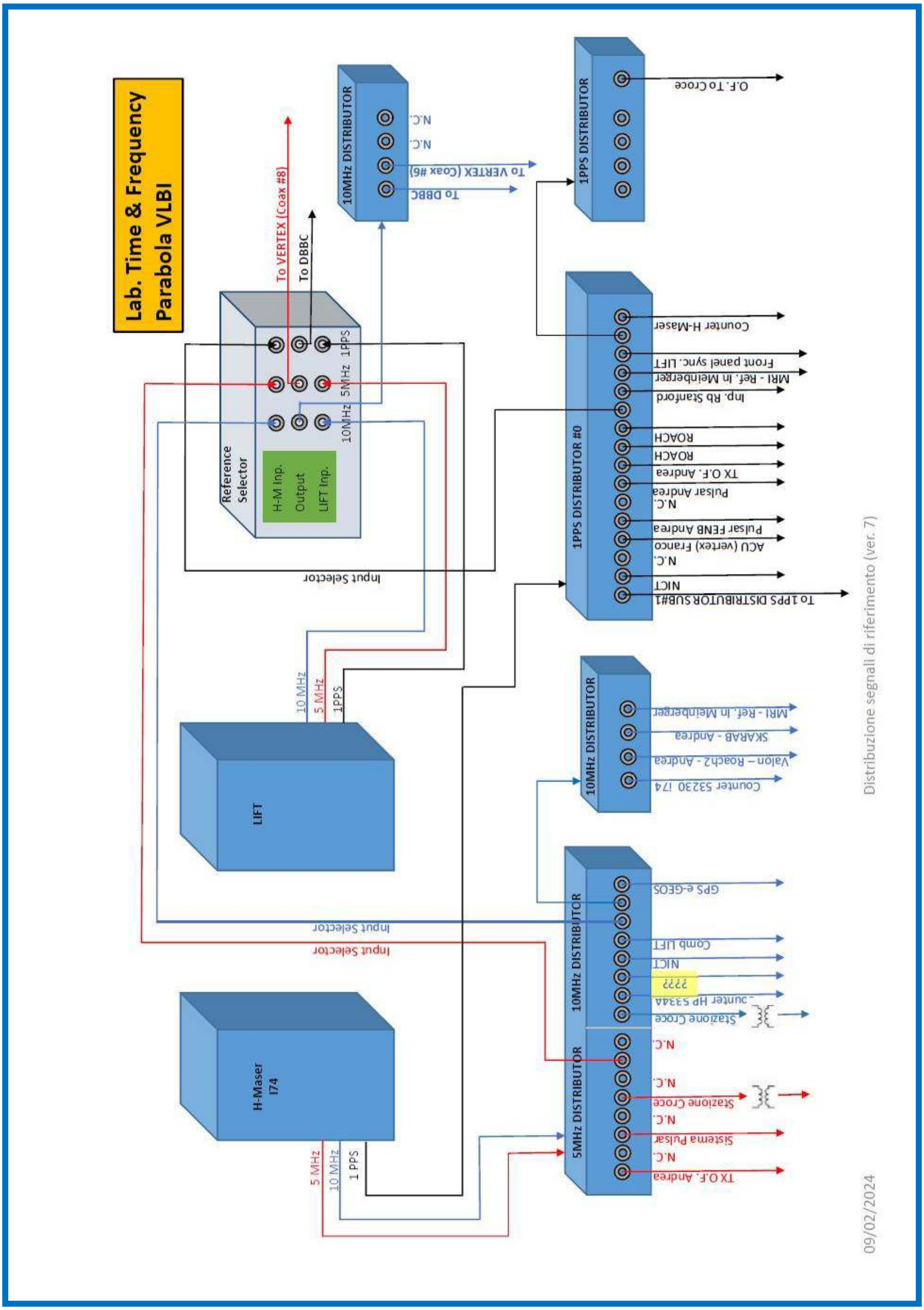
Allegato 6



Distribuzione segnali di riferimento (ver. 7)

09/02/2024

Allegato 7

VERY LONG BASELINE INTERFEROMETRY

J. Campbell
Geodetic Institute University of Bonn, Fed. Rep. of Germany

ABSTRACT

This contribution reviews the technique of Very Long Baseline Interferometry as a tool for high precision measurements of relative point positions and spatial baseline orientation. The geodetic and geophysical applications of these measurements are discussed in relation to the objectives of global and regional programs of Earth dynamics research. Following a description of the method and the instrumentation, the systematic errors limiting the accuracy of VLBI baseline vector determinations are discussed and the different approaches of error elimination are indicated. Some of the most interesting results recently obtained by the different groups involved in geodetic VLBI are shown.

1. INTRODUCTION

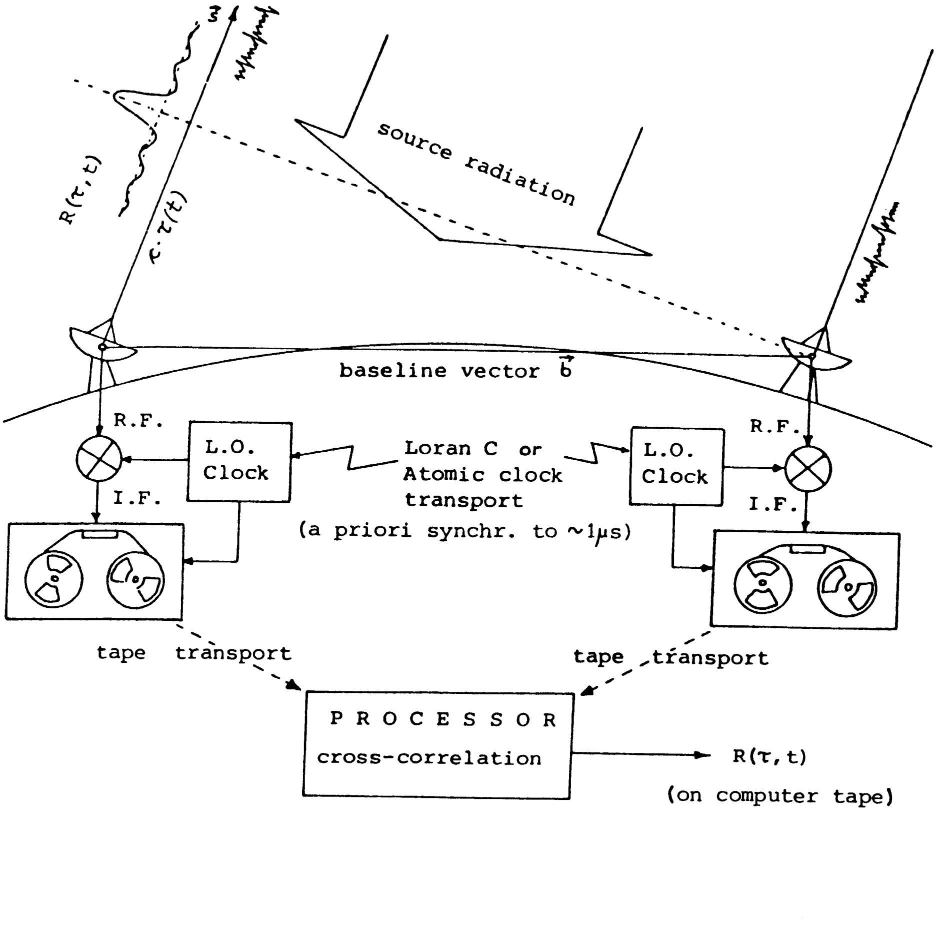
Radio interferometry originated as an astronomical observation method with the aim of increasing as much as possible the low angular resolving power of single telescopes. In its simplest form a radio interferometer consists of two antennas separated by a given distance D, the baseline, and connected via the receivers and a phase stable electrical connection to a phase meter. The response of such a system to the observed radio source carries information on its angular size and structure, which are of a prime interest to astronomers. For the study of extremely compact sources, however, the resolution of the connected element radio interferometers (CERI) proved insufficient and some means to increase the baseline length, which is proportional to the resolving power, had to be found. A major breakthrough was made in 1967, when independent stations both in Canada and in the U.S.A. were able to produce interference fringes by using very precise oscillators and tape recorders, thus eliminating the need for a cable connection (BROTEN et al. 1967[1]); BARE et al. 1967[2]). First experiments that were explicitly aimed at achieving geodetic accuracy took place in 1969 on the 845-km baseline between the Haystack Observatory, Massachusetts and the 43-m antenna of the National Radio Astronomy Observatory in Greenbank, West Virginia (HINTEREGGER et al. 1972[3])). In order to reach the high group delay resolution of ± 1 ns attained in the above experiments, a bandwidth synthesis technique had been developed (ROGERS 1970[4])). With this technique it became possible to use tape recording equipment with a limited bandwidth and sample the broadband receiver window at a set of widely spaced frequencies. Both the introduction of independent high stability frequency standards and the bandwidth synthesis technique have contributed to transform radio interferometry into a geodetic measuring system of unprecedented accuracy, now commonly known as Very Long Baseline Interferometry (VLBI).

The following description of the VLBI technique, its potential and its achievements, is primarily oriented towards the geodetic applications with emphasis on the achievement of high group delay accuracy, while omitting the astronomical source imaging techniques.

2. FUNDAMENTALS OF THE VLBI-TECHNIQUE

The most striking difference between Very Long Baseline Interferometry and other space techniques is, that the interferometric observables are obtained a posteriori by the alignment in a processor of the two identical signal streams received at different times at the two telescopes. Thus the telescopes plus the processor could be seen to embody one instrument and the baseline separating the telescope sites may be (and often is) named an instrumental calibration constant.

Fig. 1
Functional diagram of a VLBI - system



The main elements of a VLBI-system are shown in Fig. 1: The radio signals coming from a given source are observed simultaneously at two or more stations at a preselected frequency in the GHz-region, converted to baseband (video frequency) and recorded (usually in a digitized form) on high data-rate tape. Before registration the signal streams are provided with precise time information derived from the local frequency standards. Later, when the tapes are brought together in the playback processor, this permits a coherent correlation of the approximately aligned signal streams for a certain interval. Because the actual time lag is still unknown, the correlation is done at a number of different delays seperated by $\Delta\tau = 1/2B_s$ where B_s is the synthesized bandwidth of the observed channels.

During correlation the data stream from one station is delayed quasi-continuously in such a way that the changing geometric delay τ_9 is almost completely compensated for. This gives rise to a rather low residual fringe frequency, the phase of which slowly varies on the scale of a few turns per minute.

The output of the correlator is usually described by the complex cross-correlation function $R(\tau,t)$ which translates the response of an interferometer system to a radio source, see e. g. (MORAN 1976[5]).

RECEIVED SIGNALS

$$\text{Station 1} : x_1(t) = \int_{-\infty}^{+\infty} X_1 \ (\omega) \ e^{j\ (\omega - \omega_o)t} \ d\omega$$

$$\text{Station 2} : x_2(t-\tau) = \int_{-\infty}^{+\infty} X_2 \ (\omega) \ e^{j[(\omega - \omega_o)\ t - \omega\tau]} d\omega$$

CROSSCORRELATION FUNCTION $R(t,\tau_i) =$

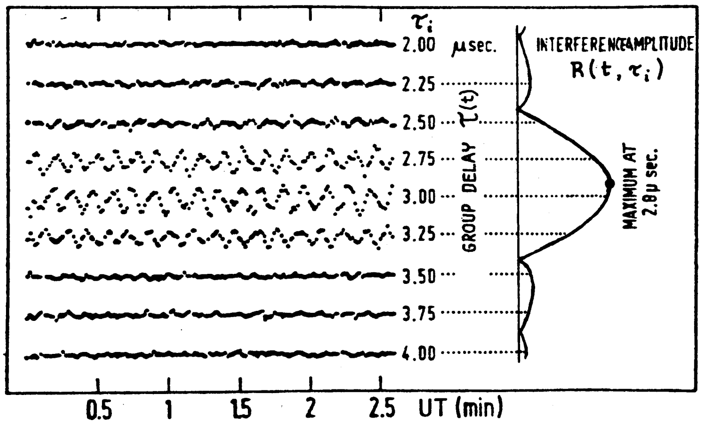
a) computed: $\frac{1}{2T}\int_{-T}^{+T} x_1(t) \ x_2 \ (t - \tau_i) \ dt$

b) model: $\underbrace{K \frac{\sin \pi \ B_s \ (\tau - \tau_i)}{\pi \ B_s \ (\tau - \tau_i)}}_{\text{amplitude term}} \ \underbrace{e^{j\ [\omega_f t \ - \ \pi B_s \ (\tau - \tau_i)]}}_{\text{phase term}}$

K = constant proportional to SNR, T = integration time
B_s= maximum spanned bandwidth, ω_f = fringe frequency,
τ = true delay, τ_i = discrete correlation lags

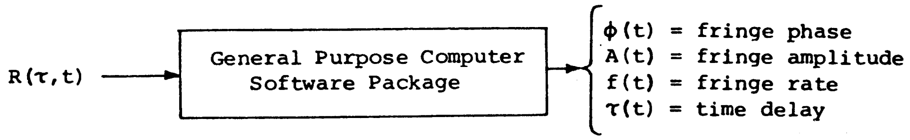
The crosscorrelation function amplitude has its first zero at $\pi B_s(\tau-\tau_i) = \pi$, hence $\Delta\tau = 1/B_s$, which is the halfwidth of the main peak.

Fig. 2
Response of a Mk II - VLBI - System to a point source



In Fig. 2 the aspect of a typical fringe pattern as produced by a single 2 MHz-channel interferometer observing a point source is shown. Here the delay spacing is 1/2 • 2 MHz = 0.25 µs.

The analysis of the fringe pattern yields a wealth of astronomical and geodetic information. As many as four - albeit partially dependent - observables can be derived from the crosscorrelation function:



The actual travelling time τ of a particular wavefront between the antennas at two sites can be expressed in two ways, i. e. as the delay of a wave group formed by the wide-band signals (group delay) and as the phase difference of a given monochromatic constituent of the signal stream (phase delay). The group delay is defined as the derivative of phase versus frequency in the band and can be estimated unambiguously by finding the maximum of the crosscorrelation function, which for an ideal square bandpass assumes the form of a sinx/x function (see amplitude term above). The delay observable yields a full baseline solution and therefore plays the most important role in geodetic VLBI.

The fringe phase and the fringe rate (fringe frequency) are obtained from the sine and cosine parts of the crosscorrelation function. Due to the close relationship of ϕ and f, these observables are determined simultaneously, either from an ordinary sine wave adjustment or using the fourier transform into the frequency domain, where the maximum of $S(f)$ is estimated. These methods, which allow to establish the function $\phi(t)$ over a certain interval of time (usually the duration of an uninterrupted source scan) are often referred to as "phase tracking" methods (THOMAS 1972[6]). In local interferometry (CERI) this method is the common way of calibrating the short baselines and measuring source positions. Due to large phase fluctuations on longer baselines the phase observable can be used in VLBI only under special conditions.

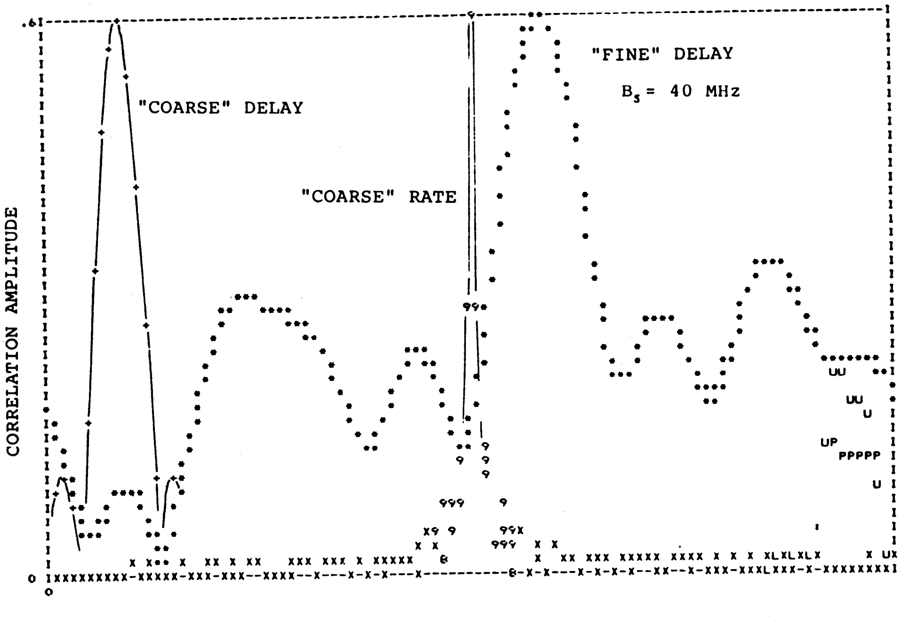
The fringe rate is unambiguous, but it is insensitive to the z-component of the baseline. So, compared to the delay observable it plays a less important role in geodetic baseline determinations.

The fringe amplitude is of essential importance for source structure mapping.

Figure 3 shows a typical example of the output of the Mk III fringe analysis software package developed by A.R. WHITNEY (1976)[7].

Fig. 3

Multichannel delay resolution function (Mk III fringe analysis)



The accuracy with which the time delay τ is estimated from the cross-correlation function depends chiefly on the halfwidth of the main peak, which is given by $\Delta\tau$ (see above).

There are different possible methods of delay estimation (WHITNEY et al. 1976[7]), all of which yield a precision σ_τ of roughly 1 % of $\Delta\tau$, depending of course on the SNR (signal to noise ratio) and the available integration time per observation.

The signal-to-noise ratio after averaging a total of $2\ B_0T$ correlated signal samples can be expressed by

$$\mathrm{SNR} = \frac{S}{2k} \cdot \frac{\sqrt{A_1 \cdot A_2}}{T_S} \cdot \sqrt{2\ B_0 T}\ ,$$

where k is Boltzmann's constant.

This expression shows that, apart from the fundamental relationship $\Delta\tau = 1/B_S$, the delay accuracy is proportional to the flux density S of a point source, the geometric mean of the antenna apertures A_1 and A_2, the square root of the recorded bandwidth B_0 and integration time T, and inversely proportional to the geometric mean of the system noise temperatures at both stations. If the ratio λ/D becomes very small, i. e. at high observing frequencies and on long baselines, many of the compact sources are resolved. This results in a marked decrease of the correlated flux density with the effect that sources which show strong fringes on baselines of a few hundred km become very weak on intercontinental baselines (see e. g. KELLERMANN et al. 1971[8]). Therefore in the latter case a high system sensitivity is of particular importance.

Efforts to improve the sensitivity of a Very-Long-Baseline interferometer have been concentrated on the sampling rate $2B_0$. With the newly developed Mk III system it is possible to record a data stream of 112 Megabit per second on 28 tracks of 2 MHz bandwidth each (CLARK 1979[9]). This has produced an increase of the sensitivity by a factor of 5.3 over the commonly used Mk II system.

The available coherent integration time T depends on the stability of the frequency standards and on the state of the atmosphere (troposhere and ionosphere). Due to the latter the ultimate stability that is achievable is limited to about 10^{-15} over time scales of $10^2 - 10^4$ seconds. Hydrogen maser frequency standards guarantee a stability of 10^{-14} over the same periods of time which is acceptable for geodetic applications. Using the above expression for the SNR the instrumental phase error

$$\sigma_\phi = (\mathrm{SNR})^{-1}$$

and the group delay error

$$\sigma_\tau = (2\pi \text{ SNR } B_s)^{-1}$$

can be computed. To illustrate these expressions, a typical example for a VLBI system consisting of two 20m antennas equipped with Mk III data acquisition terminals is given:

X - band (8.4 GHz) : 8 channels 2 MHz each; $T = 300$ sec
Correlated flux of radio sources: 1 Jansky
$\Theta_A = 0.057°$ (two antennas of 20m diameter and 50 % eff.)
$\Theta_R = 160°$ K (uncooled paramps)
SNR = 18.2 $\quad \sigma_\tau = \pm 3°$
With spanned bandwidth = 360 MHz:
$\sigma_\tau = 0.025$ ns $\quad$ ($\hat{=}0.7$ cm)

This extremely high instrumental precision is, of course, curtailed to a certain degree by systematic instrumental and environmental error sources as will be discussed later in this section.

The fundamental observation equation relating the time delay with the baseline and source vectors may be written as

$$\tau(t) = -\frac{1}{c}\,\vec{b} \cdot \vec{s}(t)$$

where

$$\vec{b} \cdot \vec{s}(t) = b_x \cos\delta \cos h + b_y \cos\delta \sin h + b_z \sin\delta$$

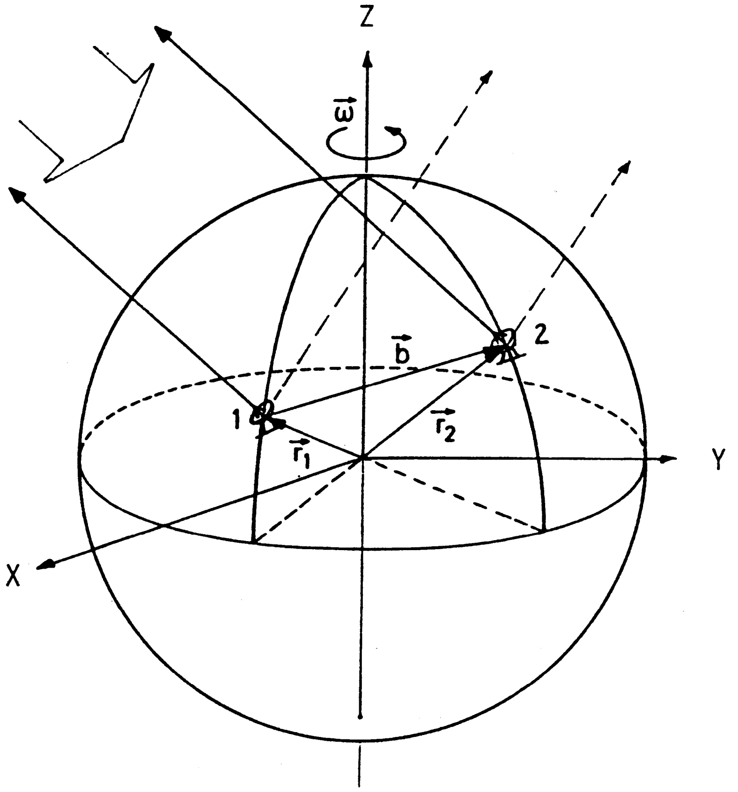
with the baseline components b_x, b_y, b_z
the radio source position α, δ
and the Greenwich hour angle of the source
$h = \text{GST} - \alpha$

The baseline vector components are referred to the instantaneous Earth rotation axis. The unit vector of the source points to the apparent position at the time of observation (see Fig. 4).

At this stage there are $3 + 2 \cdot n$ fundamental parameters to be determined in a least-squares fit: the three baseline components b_x, b_y, b_z and the coordinates α, δ of n observed sources.

In order to make theory consistent with observation, the above model has to be supplemented with terms allowing for a number of physical and instrumental effects listed below. Some of these effects can be predicted to a high degree of accuracy while others have to be parameterized or supplemented with additional measurements. In Fig. 5 an example of a geodetic VLBI software system is shown.

Fig. 4
Geometric VLBI Model



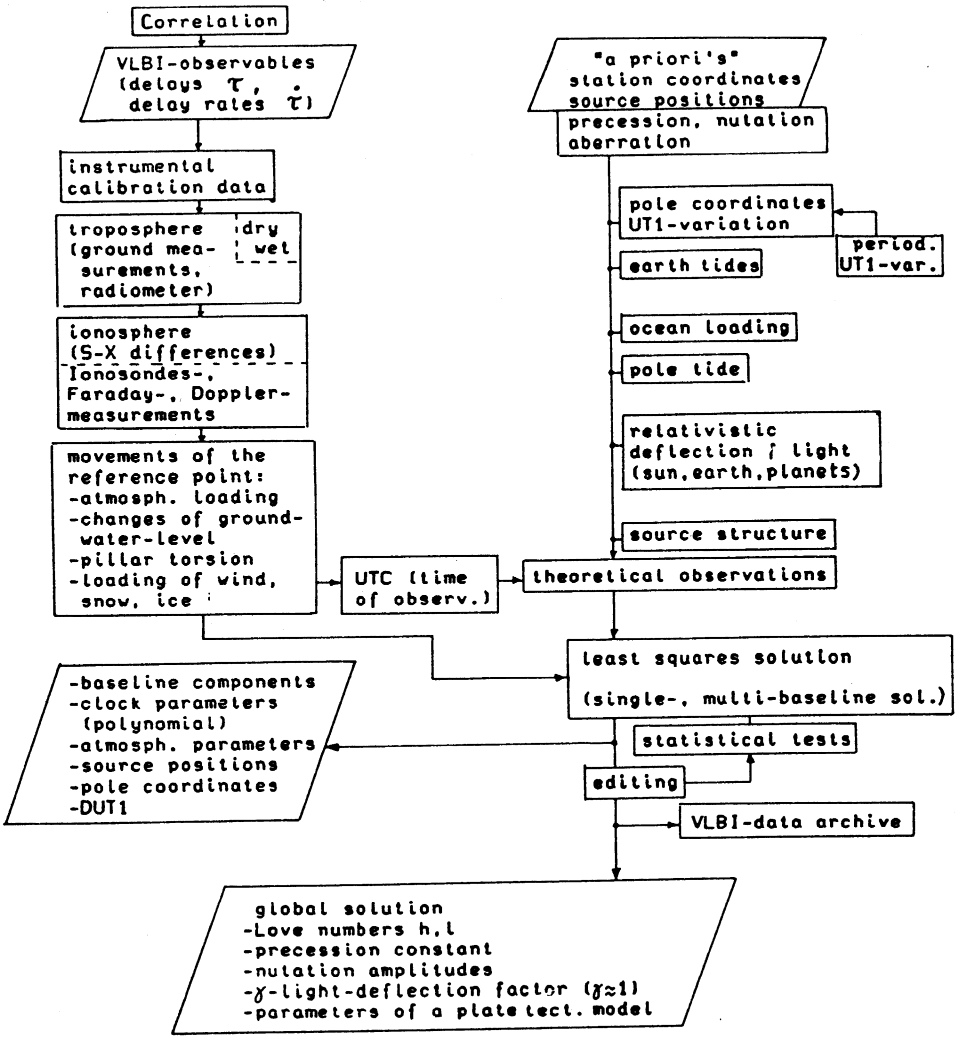
Model refinements:

a) Effects of precession and nutation

Precession and nutation are motions of the Earth's axis with respect to the celestial system represented by the positions of the observed compact radio sources. These motions are caused by external forces, the gravitational attraction of the members of the solar system, acting upon the non-spherical, inhomogeneous and visco-elastic body of the Earth. The main coefficients of the standard model have been determined empirically by long astronomical observing series and therefore are not error-free. In turn, any misalignment of the Earth's axis due to these errors will be detected by the highly sensitive VLBI observations. Significant corrections to the precession constant and to some of the nutation coefficients have been derived from the analysis of only a few years of VLBI data (HERRING et al. 1985[10]).

Fig. 5

Flow diagram of a geodetic VLBI software system



b) Relativistic effects (space-time geometry)

- special relativity. Due to the relative motion of the VLBI antennas during observation the finite speed of light causes significant additional delays which can be precisely modelled (diurnal aberration etc.).
- general relativity. The effect of gravity on the propagation of electromagnetic waves is considerable (near the sun the delay may be many orders of magnitude larger than the measurement error). VLBI observations have been used to verify Einstein's theory to an accuracy of about 0.1 %.

c) Instrumental effects

- local oscillator instabilities. Usually a clock model is introduced that accounts for the unknown epoch difference and a differential drift rate (two parameters). Unmodelled clock offsets and rates may lead to large systematic errors especially in the z-component of the baseline.
- change in the electronic circuitry and cable delays. While a constant delay is absorbed by the clock offset parameter, any delay changes have to be monitored by a phase and delay calibration system.
- deformations of the telescope structure, displacements of the reference points. These effects can be checked by models supplied with local geodetic measurements.

d) Environmental effects

The effect of the atmosphere on VLBI-observations is considered the most serious problem, because at widely separated stations the look-angles of the telescopes aimed at the same source differ greatly as well as the meteorological conditions themselves. The <u>ionosphere</u>, which is a highly dispersive medium for radiation in the radio frequency band, can be dealt with by using two different observing frequencies. Moreover, its influence diminishes considerably with increasing frequency. At 8 GHz the extra-zenital path due to the ionosphere reduces to about 2 dm. The remaining effect, however, is very unstable; therefore the dual frequency method using a second frequency at 2.3 GHz is applied. The neutral atmosphere, essentially the <u>troposphere</u>, presents the same problems in VLBI as in Doppler and radar satellite observations. Its influence on radio signals adds up to an extra-zenital path of 2.0 - 2.5 m. The contribution of the dry air is rather stable and can be described by suitable models. The wet component, although much smaller, changes rapidly and has to be monitored during the observations. The most promising method appears to be the radiometer technique, which consists of measuring the micro-wave thermal emission from water vapor near 22 GHz in the line-of-sight.

e) Geophysical effects

- polar motion and UT1-variations. These are effects that change the components of the baseline but not its length. To a certain degree of accuracy ($\sim$1 m) these variations can be obtained from the regularly published bulletins of the BIH to apply "corrections" to the observables (or to the model). In recent years the observations have proven to be more accurate than the corrections. Therefore the problem has been inverted, the changes showing in the baseline components being used as precise polar motion and Earth rotation data.

- Earth tides. The tides of the solid Earth are mainly semidiurnal and diurnal effects of a few decimeters in amplitude that change the baseline components as well as the length. The solid Earth tides are predictable to a few cm, but it is also possible to derive significant estimates of Love's numbers from VLBI observations. For stations close to the shores an additional correction due to the ocean tides has recently been included in the model.
- crustal motions. The theory of plate tectonics which stipulates that the Earth's crust is formed by a mosaic of separate plates that are in motion relative to each other has now been universally accepted. Predictions derived from geophysical evidence yield motions of a few centimeters per year. These small displacements constitute one of the main interests of a continued series of VLBI experiments aimed at the detection of the present rates of motion.

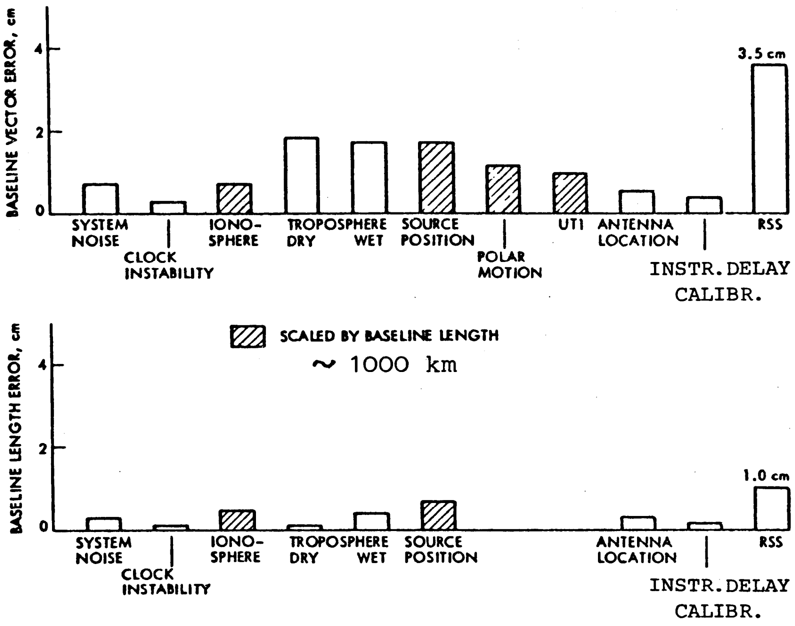
f) Radio-astrometric effects

- Precise source positions are usually determined simultaneously with the baseline components. Even so, special astrometric campaigns are carried out in order to establish consistent radio-source catalogues for fundamental astronomy, optical counterpart identification and for the support of geodetic programs. The accuracy of some thirty compact radio sources, most of which are located in the northern hemisphere, is now at a level of 2 - 3 milliarcseconds as determined from VLBI-experiments. Work is in progress to improve the source coverage over the sky and to provide a firm connection to the existing optical reference system.
- Most of the observed compact sources tend to show structure at the level of a few milliarcseconds. This effect, in particular any changes in the structure, poses a limit on the accuracy of the radio-reference system. Permanent monitoring of the structure, which can be done by using the geodetic VLBI data, will help to reduce the contribution of these errors in the future.

The total geodetic error budget on baselines of about 1000 km sums up to about 1 cm in length and 3.5 cm in the individual components (see Fig. 6). Intercontinental baselines of about 6000 km show errors of 2 - 3 cm in length and 10 cm in the components. These extremely high accuracies (~ 0.01 ppm) form the basis of the increasing efforts invested in the use of the VLBI-technique for the determination of such subtle effects as variations in the Earth's rotation and crustal motion.

Fig. 6

Error Budget of Geodetic VLBI Accuracy



2. SCIENTIFIC INTEREST; PROGRAMS AND RESULTS

A detailed description of the geophysical applications of VLBI has been presented as early as 1969 at a conference held in London, Canada on "Earthquake displacement fields and the rotation of the Earth" (SHAPIRO, KNIGHT 1970[11]). In subsequent years virtually all of the goals could be realized or at least reach the stage of initial successful verification. In the following paragraph the scientific goals and projects are summarised and some of the recent results of the ongoing campaigns are shown.

Geodetic and geophysical interest in VLBI is based fundamentally on the use of an inertial reference frame of highly compact extragalactic radio sources. With the VLBI-technique it is possible to measure very accurately the baseline vectors and their changes in time between distant points on the Earth's crust. Therefore the primary objectives to use VLBI observations are:

1. the realization of a unified global reference system in order to satisfy the needs of global geodetic and navigational systems;
2. the monitoring of polar motion and changes in the Earth's rotation rate to enable a better understanding of the kinematics and dynamics of the Earth-Moon system and the structure of the Earth's interior;
3. the estimation of the Earth's elasticity parameters from directly measured tidal deformations;
4. the determination of plate motion and plate stability to improve the understanding of global plate tectonics;

5. the investigation of regional crustal movements in order to deduce the building up of strain and provide input to earthquake prediction programs.

Other important activities are:

6. the determination of improved values for the precession and nutation constants, and
7. the precise verification of the effects of general relativity.

The accuracy requirements necessary to attain these goals are ± 5 to ± 10 cm in each baseline component for items 1 and 2 (± 0.1 ms for UT1) and ± 1 to ± 3 cm in baseline length repeatability for items 3 through 5. By now these accuracies have been demonstrated in hundreds of VLBI campaigns on baselines connecting nearly all major continents of the globe.

Corresponding to the international nature of the anticipated goals several programs of multilateral cooperation have been initiated, among which the following most important projects should be mentioned:

1. NASA Crustal Dynamics Project (CDP).
   This project is part of a US Federal program involving several government agencies for the application of space technology to crustal dynamics and earthquake research. Major cooperative arrangements have been made with European and other countries extending the project to a global research program (NASA 1983[12]).

   The VLBI part of the CDP comprises regular experiments (10 - 20 a year) of one to three days duration between the major geodetic VLBI facilities in the US, Europe and in and around the northern Pacific. In addition, so-called bursts of observations using the mobile VLBI units are carried out each year in the tectonically active zones of California and Alaska. These campaigns are aimed at the creation of a detailed picture of the local crustal motion pattern to assist the investigation of earthquake mechanisms.

   The global station distribution is shown in Fig. 7. Some of the stations are still in the process of being fully equipped for Mk III VLBI.

   The CDP in its present form is planned to extend through 1988. Follow-up programs will be set up in order to insure the repetition of the measurements at regular intervals of one or two years.

2. Project IRIS (International Radio Interferometric Surveying).
   The goal of project IRIS is to conduct joint activities between the NGS-(US National Geodetic Survey) POLARIS-Network and other international stations that are dedicated to full-time geodetic work, such as the VLBI-station of Wettzell, for the regular monitoring of Polar Motion and UT1.

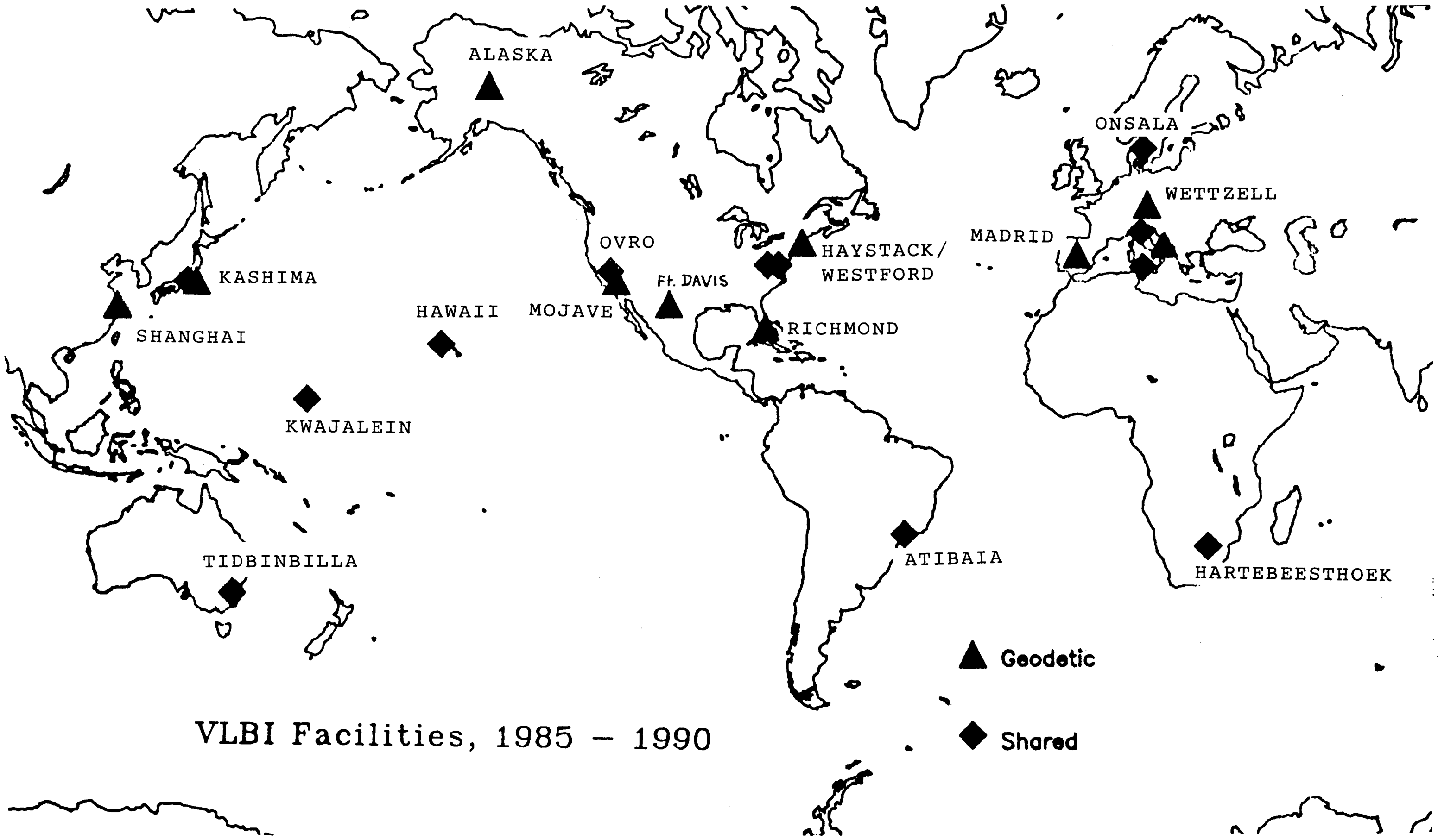
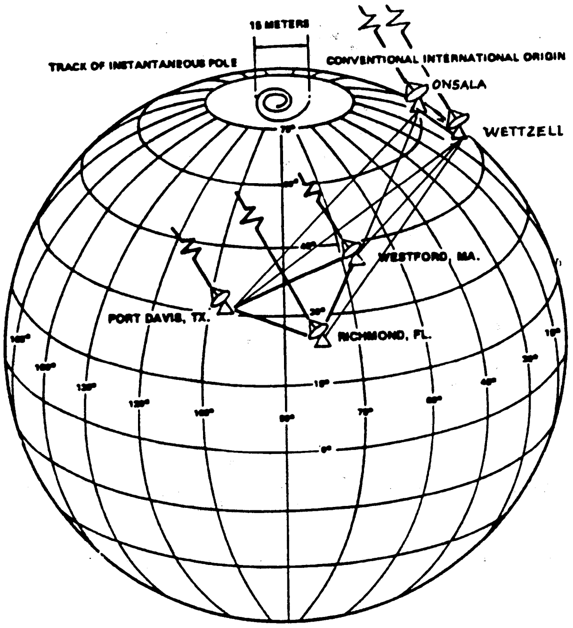


Fig. 7 Global VLBI network

The IRIS activities consist of a series of VLBI observing sessions of 24 hours duration at five-day intervals. The IRIS observations normally involve three stations in the United States (the Westford telescope in Massachusetts, the George R. Agassiz Station (Ft. Davis) in Texas and the Richmond Observatory in Florida) and the 20 m radiotelescope of the Wettzell Observatory in the Federal Republic of Germany. One session per month also includes the Onsala Space Observatory in Sweden (see Fig. 8).

Fig. 8
IRIS earth rotation network

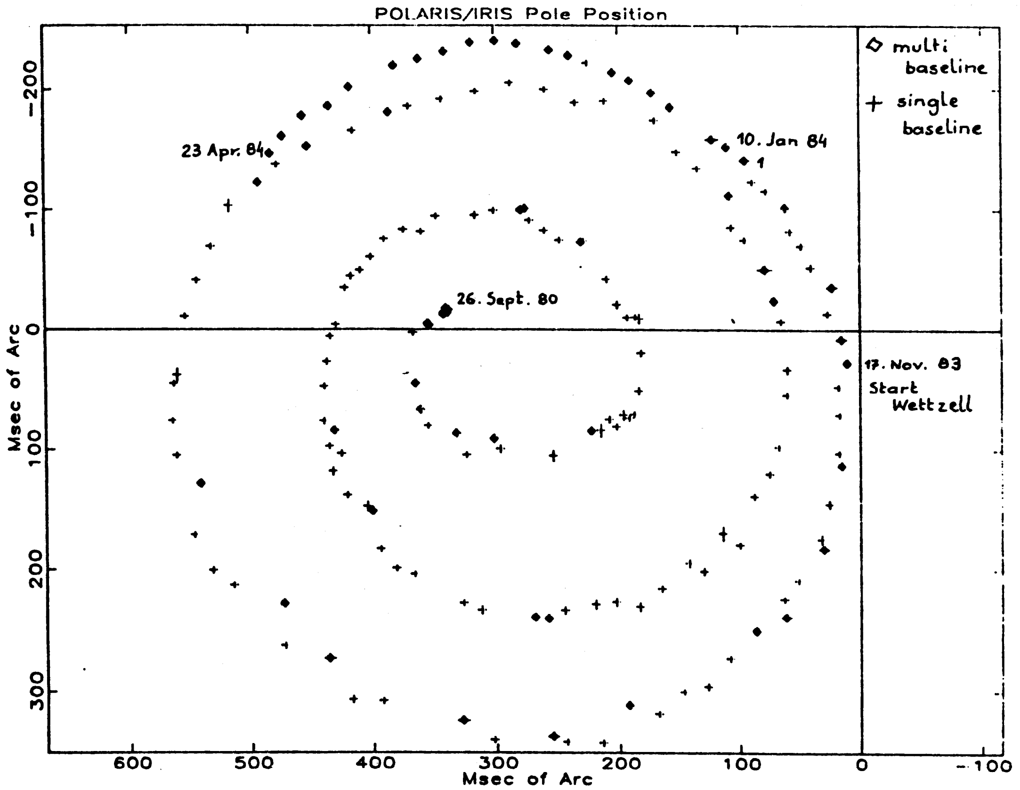


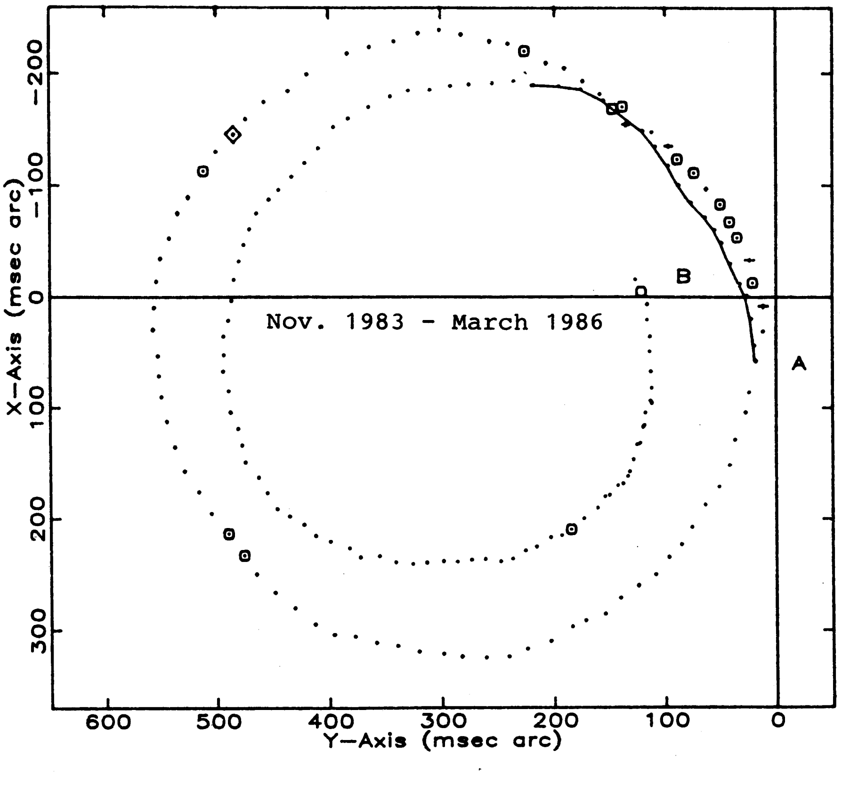
The National Geodetic Survey (NGS)/Rockville, Md. regularly analyses all of the IRIS data to obtain polar motion and UT1 time series, which are published monthly in the IRIS Bulletins A. Thus, since Jan. 5, 1984, the date that the Wettzell Observatory began regular operations, the IRIS system has been routinely providing the x and y components of polar motion with an accuracy of 1 to 2 marcsecs, and UT1 with an accuracy of 0.04 to 0.1 msecs (CARTER, ROBERTSON, MACKAY, 1985[13]).

Figures 9 and 10 show the remarkably smooth trace of the instantaneous pole of rotation from Sept. 26, 1980 (the time of the MERIT preliminary campaign) until March 15, 1986. In particular, a significant improvement of accuracy can be seen from the moment that the full IRIS network with the station of Wettzell has become operational in January 1984 (Fig. 10).

In addition to the regular 5-day observations a special campaign of daily observations on the baseline Westford - Wettzell is being performed

Figs. 9 and 10
Merit and POLARIS/IRIS pole position
Sept. 1980 - April 1984





with the aim of looking at the short period UT1-variations. A frequency analysis on 90 days of daily VLBI observations already permitted the detection of the predicted 13.6 day and 9.1 day periods caused by tidal deformation of the polar moment of inertia of the Earth (Fig. 11). Both the amplitudes (0.9 and 0.2 msec) and phases are in good agreement with the theoretical values. These results represent a first purely empirical confirmation of theoretically derived short period tidal oscillations in the Earth's rotational speed, which until now had been hidden in the noise and the poor temporal resolution of the BIH data (ROBERTSON et al. 1985[14]), CAMPBELL, SCHUH 1986[15]).

The NASA-CDP and the IRIS VLBI campaigns have been providing baseline length results since the late seventies when the Mk III VLBI system became fully operational. As the length of a baseline vector is independent from changes in its orientation, the observed baseline length series are free from errors in the Earth rotation parameters and can be treated as an independent result of the campaign. However, as has been shown in the error budget (Fig. 6), other factors such as source positions (including the associated precession and nutation models) and atmospheric effects may still cause problems when long series are to be interpreted. At present only two baselines across the Atlantic (Onsala - Haystack and Onsala - Westford) cover a long enough period (4 years) to be able to make first estimations of a meaningful relative motion. Both indepently observed series seem to indicate the same annual drift rate of 1 - 2 cm per year between the North-American and the Eurasian plate (Fig. 12). Before any firm conclusions can be drawn the further evolution of the much more frequently observed baseline Westford - Wettzell should be awaited. The continental baseline Westford - GRAS (Ft. Davis, Texas) also shows an appreciable change, which could confirm theories of an elastic behaviour of the plates.

While the North-Atlantic section of the CDP and IRIS networks has been observed on a routine basis, great efforts are made to include new stations, in particular Shanghai, China, Hartebeesthoek, South Africa and Atibaia, Brazil (Fig. 7). The stations of Kashima, Japan and Kauai, Hawaii have been active since the beginning of 1984. On this baseline, where large motions are expected, a contraction of 5 cm per year has been derived from the first two epochs. The length variation on another Pacific baseline, Kashima - Kwajalein, of -8 cm in one year is the largest so far observed. The agreement of these observations with the predicted rates derived from geophysical evidence is very good (KONDO, HEKI, TAKAHASHI, 1986[16])).

Thus in recent years the VLBI technique has lived up to its expectations. By now large amounts of data have proven conclusively that the anticipated accuracy levels can be effectively realized in routine observing campaigns.

Fig. 11
Short period UT1 variations
(obtained form 90 days of daily VLBI observations)

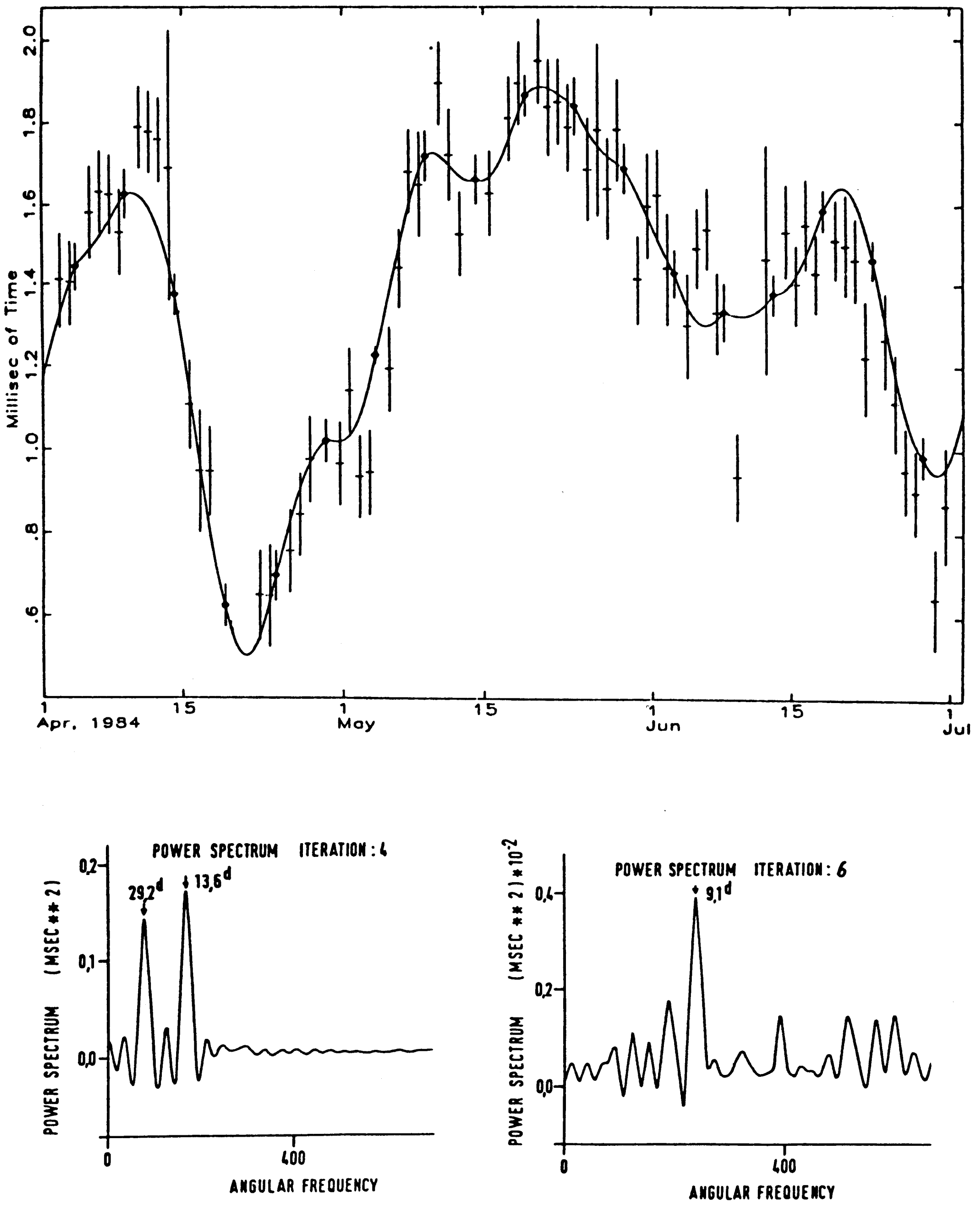
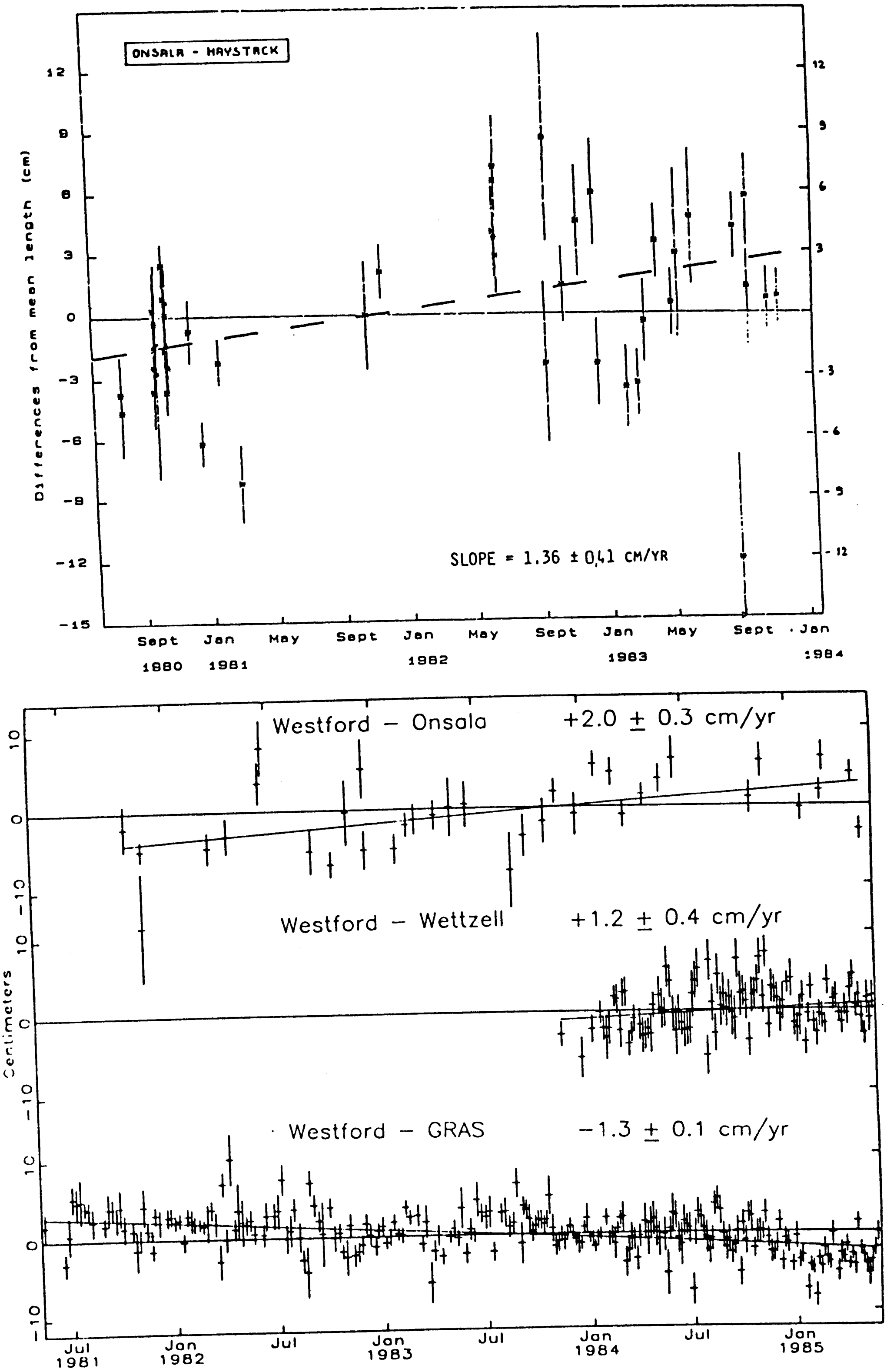


Fig. 12
Transcontinental and intercontinental baseline evolution 1981 - 1985



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