# ArraySi gnal Processingin theNASADeepSpac eNetwo rk

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*Abstract*— The NASA Deep Space Network (DSN) has recently been augmented with an array capability. This is a third-generation system employing the full spectrum combining technique. The first deployment at Canberra, Australia in 1996 was made specifically to support Galileo mission; the second deployment at Goldstone, California, U.S., followed four years later in 2000 and was of multi-mission capability. The third installation extended the Goldstone capability to the other two DSN sites, namely Canberra,Au straliaan d Madrid, Spain.

The new array capability offers many benefits to deep space missions whose signal reception is often constrained by the vast interplanetary distance. With an increase in signal level obtained from combining the inputs of several smaller antennas, the new capability helps to extend the mission life time for those whose received reception from a single antenna falls below the tracking threshold. For other missions not constrained by this problem, arraying can help to increase telemetry data return relative to that received from a single antenna. Aside from benefiting telemetry data, for the first time in the DSN history, arraying via full spectrum combining technique also enhance navigation performance.

In this paper, we will describe the benefits of arraying and past as well as expected future use of this application. The signal processing aspects of array system are described. Field measurements via actual tracking spacecraft are also presented.

TABLEO FC ONTENTS



## 1. INTRODUCTION

Arrayingis acom mont echniqueu sedto im proverecepti on of weak signals[1 ]. Itis sy mbolically representedin Fig ure 1.Th esi gnals receiveds imultaneouslyfr omd ifferent antennasareco mbined,creat ing the sameeffectas an enlargedap erture. This approachcan be ofb enefitin d eep spacec ommunications where thes pacecrafttran smitted signalis s everelyatte nuatedas itt ravelsacro ssv ast interplanetary distances.

Thisp aper firstp rovidesan h istoricalcon textfo r the developmentan d applicationo farr aying.It thenfol lows with asy stem descriptionan dhi ghlights ofd ifferentas pects of signalp rocessing. Alsop resentedareth eresul ts obtainedfrom fiel d measurementon k eyp erformance parameters.

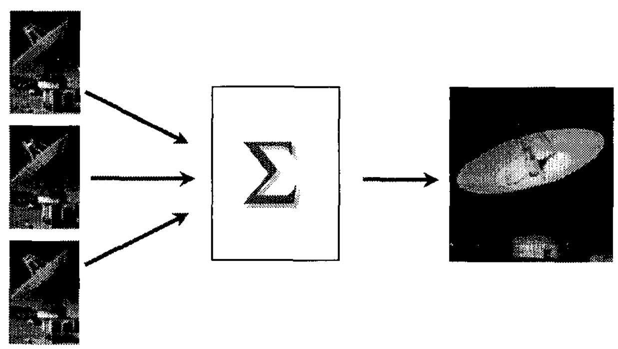


**Figure 1**B enefito far raying

## 2. PAST AND FUTUREUSEOF AR RAYING

In the past,t heVo yager missionreli ed onarr ayingto increaseit sd ata return duringUranu s encounterin 1 986 and Neptuneen counteri n1 989[2, 3].Th eGal ileom issionw as anotherrecen tex amplewh erearr ayingwas used to significantly increaset he scienced ataretu rn.Th earr aying employedu pt ofiv ean tennas,lo catedat th reedi fferent trackingfaci litiesan d spreado ver the twoco ntinentso f North Americaand Au stralia. Itresu ltedi na factoro f3 improvementi nd ata return.[ 4,5 ,6 ]

Future missions cana lsob enefitfr omarray ing. Thes e include theclass o fm issionswh erecertain o perational phasesm ayreq uire moreperform anceth ana sin glean tenna canpro vide. Forex ample,th eC assinim ission requireso nly single3 4-meteran tenna supportd uringcr uiseperio d,bu t uponen teringSatu rno rbit,in o rderto r eturn 4G bits/day mappingdat a(averagi ng4 6k bits/s), it requiresth eus eof anar rayo fa7 0-meteran da 34-meterant enna[7] .An other classofp otentialm issionsis th oseth atn eedto relay c ritical sciencedat ab ack to Earth in the shortestam ount oft imeas possible. Stardustbel ongsto th isgro upo f customers. Uponenco untering theW ild2 com etin 20 04an dh aving analyzedth ep roperty ofco metarysam ples,th em ission plansto redu ces ingle-eventrisk sb ys ending databack as fastas possible [8]. An arrayo f two34 -meter antennasw ill enableth eS tardust missionto cu tt het ransmissionti mein halfco mpared toa sin gle-antenna.

In the DSN,th e7 0-meteran tenna, being the largesttrac king station, iso ften relied onfo r trackingsp acecraftin th e outermostregio nofd eepsp ace. This an tenna,h owever, wasb uiltin th elate1 960's. Asth ean tennastru ctureag es andreq uiresm orem aintenanceserv ice, therei sa growing *concernrega rdingit sav ailability.*An array o fs everal smaller3 4-mant ennascan serve asab ackupfort he 70-meterd uringext endedm aintenanced owntime.[1]

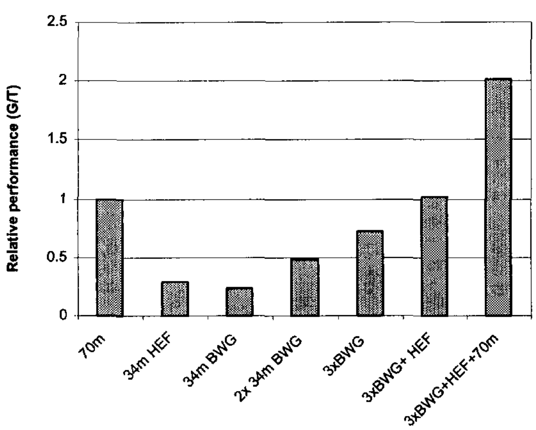


**Figure 2**R elativep erformance ofarray ing.

Another way of looking at the issue is that arraying increases the flexibility of DSN scheduling and allows for better utilization of available resource. In the absence of an arraying capability, a shortfall in 34-meter link performance willrequ irethe useo fth e70 -meter. Asaresu lt, theree xists a potential for over-subscription of the 70-meter antenna service. With arraying, however, the DSN has the option to schedule additional 34-meter antennas incrementally to meet mission requirements. Figure 2 provides a comparison on the relative performance, in terms of gain-to-noise-temperature ratio (G/T), of different array configurations[2]. Note that an array of four 34-meter antennas will give the same performanceas the7 0-meter.

3. MER ITSOFF ULLSPEC TRUMAR RAYING

Them ainob jectiveo f arrayingis to coherentlyco mbine signals fromdi fferentan tennas;h owever,b ecauset he antennasareg eographicallysep arated,t he signalreceiv edat eachsi teh asa differentd elay andDo ppler which are dependento nth eant enna'sp ositionan dm otion relativet o thes pacecraft.Th ed ifferential delay andDo ppler must be removed soth atal ld ata streamsc anb eco herently combined. Int he arraying techniquesd escribed below, thesequ antitiesare modeled, andth en the residuals between them odelsan d the actualv aluesareo btainedb y cross-correlatingth ed atas treams frompai rso f antennas.

Thesi gnalu sed in deeps paceco mmunicationsty pically consistso fasi nusoidal carrier, asq uares ub-carrier thatis phase modulated ontoth ecarr ier,an dt elemetry symbols thatare, in turn,p hasem odulatedo nto the sub-carrier.Th e processofcro ss correlationan dcom biningcan b ed oneat differentl evels:sy mbol,carr ier,o r acrossth ewh ole spectrum [9,10,11,12].F igure3 illustratest het hree differents chemes.Th earr ay implementation describedin thispap erem ploysth eful ls pectrumm ethod. Int he followingp aragraphs, weh ighlightt herela tivem erits betweenth is techniqueand o ther commonlyu sedo nes.

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[1]Its hould ben oted thatthe 70-msu bstitution,o r otherarray usage discussed in this paper, refers only to downlink processing. The capability, as built, does not support an arrayedu plink.

[2] Among the six antennas capable of receiving X-band at Goldstone, the largest being the single 70-meter antenna and the rest 34-meter's. The 34-meter group is further categorizedint oh ighef ficiency(HEF) an db eam waveguide (BWG) dueto d ifferencesi nt heird esignan dp erformance

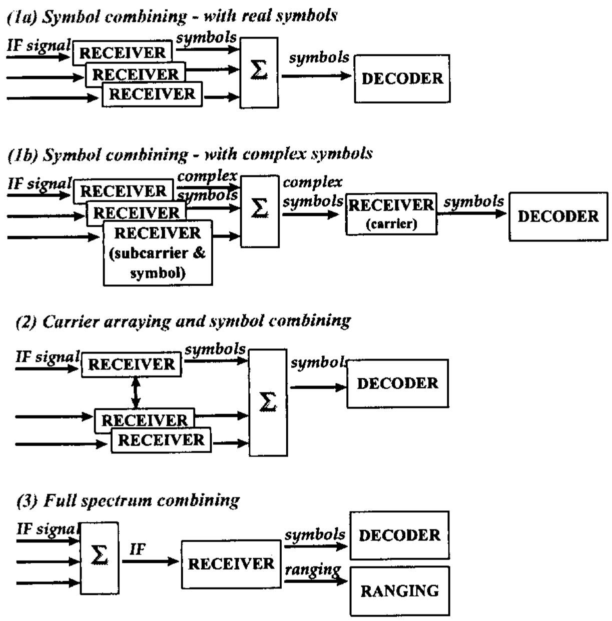



**Figure** 3Di fferentar rayingm ethods

*SymbolC ombining*

Ins ymbolco mbining, demodulatedsy mbolsfr omd ifferent antennasared elayco mpensated,c ross-correlated, and finallyco mbined.C ombing canb ed onewi thr ealo r complexsy mbols. The resulting signalh asah igheren ergy per bitto noisesp ectral densityrat io (Eb/No),t husreal izing alo werb iterrorrate performance.Th us,t hec ombined signalal lowsforp roperd ecodingo ftel emetryin formation whereasin dividuals ymbolst reams wouldn ot.Thi s techniquew assu ccessfullyu sedin th eVo yagerm ission.

The symbolco mbiningtech niqueo ffersan ad vantageo f doingsi gnalp rocessing atrelat ivelylo ws ymbolrates , typicallyin th erang eo ften st oh undreds ofk Hz. Requirementso nth eaccu racyofd ata alignmentare thereforeles sco nstrained.Trans portingofs ymbols treams tob eco mbinedo ver longd istance is alsoeas ier,t hus, allowingant ennas atl arge distancet op articipatein th e array.

A drawback, however, is that it requires the signal level at individual antennas to be well above the threshold of the receiver.O therwise,v alid symbolscan notb ed erived.

*Carrier arrayinga ndsymb olco mbining*

In carrierarrayi ng, informationd erivedfr omth ecarr ier signald etected atth em ainan tennais us edto ach ieve acquisitionatth es upportingan tenna.On ceb oth receivers lock up,s ymbolstream s cant henb eco mbined.

The advantageofcarrierarray ingi st hat it pushesd own the signalt hresholdrequ iredf orno rmalo peration.On ly the referencean tennain th earray m ustacq uire the signalo n its own.

*Fulls pectrumco mbining*

In fulls pectrumco mbining, theen tires ignalsp ectrum of interestco ntainingth ecarrier,su b-carrieran d symboli s combinedal lat on ce. Du ringarang ingsess ion,th er anging signals haring thiss pectrumis alsoco mbined.Th eres ult is anim provementi n radiometrico bservablesas well .C arrier demodulationt ogetherw ithsu b-carrier andsy mbol synchronizationtak es placeo nly aftersi gnals areco mbined. Them ain advantage offu ll spectrum combining is a loweringo fth eacqu isitionth resholdrequ iredi n the receiver,deco der and rangingco rrelator.

Thech allenge ofsp ectrumcom bining is in the correlation process. The errorin th ees timationofrel ativede lay betweenp airso f antennas becomesm ore pronouncedsin ce processingn ow appliesto IFfr equency,w hichi sh igher than symbolfrequ ency.

Fulls pectrumarray ingw asfi rstem ployedin th eG alileo mission. The Galileo su pporteq uipment,h owever, is tailoredto lowda tarates (bel ow1 k sym/s). Then ew capabilityde scribedi nt hisp aperex tendsth es upportedd ata rateto 6 Ms ym/s.U nfortunately,b ecause ofth eh igh transmission bandwidthb etweenth ean tennasn eeded at thesehi ghdat arate s, thearray is lim itedt ot hosea ntennas withinat racking complex,i.e. , no inter-complexa rraying across two continentsis su pported,as in th ecas eo f Galileo arraying.

In summary, symbol combining is achievable as long as individual antennas in the array can acquire and demodulate the signal. Its benefit, thus, applies mostly to the decoding process. Carrier arrayinghel ps to overcome thesho rtfallin the receivercar rier-trackingl oopat thesu pportinganten nas. Full spectrum arraying further reduces the required threshold, enabling proper demodulation of the combined signal,bu t such processing cannot be doneon thein dividual signals.

## 4.EQUIPM ENTDESC RIPTION

Signalp rocessingforarray ingi sd oneb ytwo m ain assemblies-th eF ullSp ectrumRece iver (FSR) andth eF ull Spectrum Combiner(FSC ),see Figure4 . The FSRin puts arein dividual3 00M HzIFs ignalsd erivedfrom th eR Ft hat have beenreceiv edb y the antenna,a mplifiedb y the microwaveeq uipment,an d downconvertedby anR F-to-IF downconverter.Th eFSR o utputsaredi gitalsam plesat 1 6 MHz,8 -bit resolution.O nce digitallyco mbinedb yth e FSC, the signali sco nvertedb ackt oan alogform .Ex cept forh avingah igherS NR,th esi gnali sv irtuallyid enticalt o thes ignalarriv es atth ereferenc ean tenna.Do wnstream processing(su ch asd emodulation,d ecoding, andrang e detection)ca nt henb eacco mplishedo nth ecom bined outputi no rderto y ieldfi nal sciencean d engineeringdat a products.

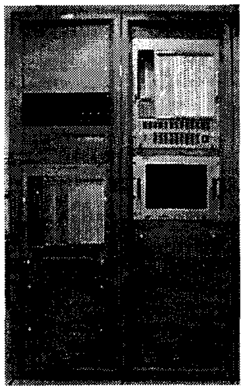


**Figure 4**Array si gnalp rocessingeq uipment

Majorco mponentsof the FSRareillu stratedin F igure5 . The analog/digitalcon verter andth edi gitaldo wnconverter capturerele vantp ortions ofth e3 00M HzIFan alogs ignal inal 6 MHz, 8-bits ampled, in-phaseand q uadrature-phase digitald atas tream. The del ay linean dp hasero tator boards correct signaldel ayan dp haseu singin formationfrom predictst ogether withfeed backfr omth eFSC d erived residuals.Th es ignalm onitorb oardsam ples thedi gitald ata streams andtran sformsthe m tom easurementso fcarrier and telemetry signal-to-noiseratio s (SNRs). Thesev aluesare providedt oo peratorsform onitoring.Th eyarealso relay ed toth eFS Cfo rprop ers etting ofth ecom bining coefficients. Measuremento fth ecarrierSN Ris o btainable directlyfr om thest andard FastFo urier transform.Meas uremento f the telemetrySNR , however,req uiresso mem anipulation involving the correlationoft heu pperand l owerh armonics oft hes ubcarrier. The Realtimean dD atap rocessorsh andle high-levelm onitoran d controlsi nt heFS R.

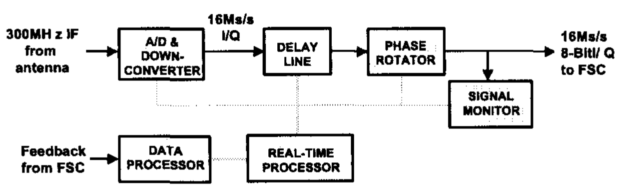



**Fig ure5** Pro cessing in the full spectrumreceiv er.

Figure 6 presents major components in the FSC. The cross correlations of upper and lower sideband of different antennas are used to derive differential phase and delay values for feedback to the FSRs. At the same time, the Weight and Sum combine the weighted FSRs input, to produce optimal output. The D/A and Upconverter transforms the digital baseband stream to an analog 300 MHz IF. The Signal Monitor as well as the Realtime and Data processors carry out functions similar to those in the FSR.

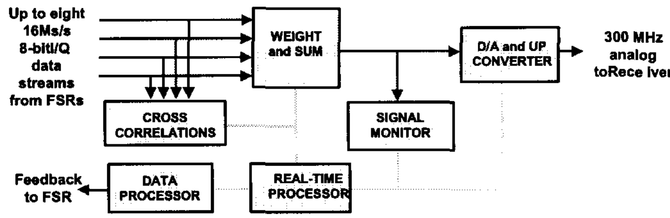



**Figure 6**Pro cessingi nt hefu ll spectrumc ombiner

## 5. SIGNALP ROCESSING

Thiss ectionwi llh ighlightso meas pects ofth esi gnal processingu sedin arr aying. Them ainfo cus is on correlation, delaycom pensation andcom bining.

### *Correlation*

The successo fcom biningd ependso ng oodco rrelation results.C orrelationi san ess ential processw ithout which properco mbiningcan not bed one.

Figure 7s hows the detailedp rocessing ofco rrelation.Wi th theaid ing ofDo pplerp redicts,th eup per(UPR )an dl ower (LWR) sidebandso fth es ignal receivedateach an tennaare captured.Th eup per sidebandf romon ean tenna is correlatedwit h the sameco mponento fth earray ref erence, fromwh icht hep hased ifferenceat th eu pper sidebandis measured. The samep rocessis si multaneously performed ont hel owers ideband component.An av erageo f the two phasem easurementsth eny ieldsth ep haseo ffset, whileth e ratioo fth eird ifferenceto tw iceth es ideband frequency providest het imed elay.

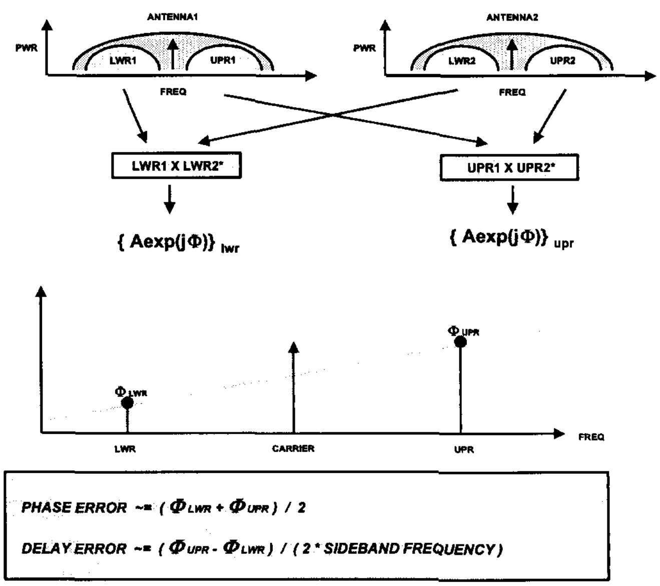



**Figure 7**C orrelationp rocessing

There aredi fferentway so fim plementingt hec orrelation process.Th eful lsp ectrum arraying equipment supports twoap proaches,bo ths uccessfully tested. The simpler scheme("si mple")in volves choosing the antennas ignal of largest SNRto b eth ereferenc e,ag ainst whichal lo ther antennas ignalsareco rrelated.Th iss chemewo rks well whenon ee lemento fth ea rray hasasi gnificantly higher SNRth anth eo thers,as in thecase ofarrayi ngth e7 0-man d 34-meteran tennas. Thes econd method,refer enced as "sumple", treatst he arrayreferen ceas aro tatingsu mo f all antennasexcep t the oneu nder consideration.In ot her words,o nea ntenna will be cross-correlateda gainst the sum ofa llo thers. Sim ulation resultsin dicatet hat the rotating summ ethodp erformsbet terth anth efixed refer ence,an d thatth efin al solutionem ergeswi thina fewit erations,s ee Figure8 [13]. No teth at the simulationi ncludesa third approachu sing eigenv aluem ethod[14 ];ho wever, this algorithmis no ti mplementedin th eFS C.

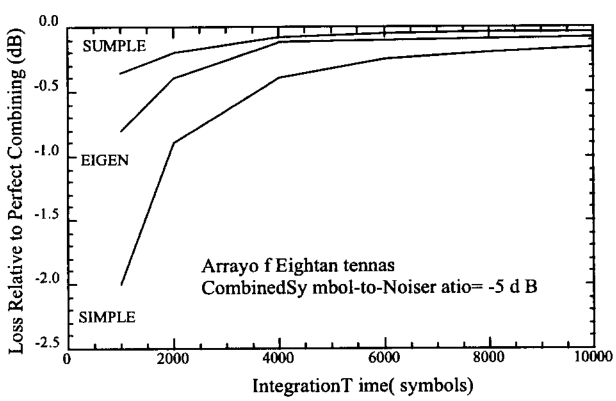



**Figure 8**Di fferentm ethodso f correlation

Consideration needs to be given to the setting of integration time for the correlation process. From thermal noise considerations, a long integration period is preferredsin ce it wouldy ield an estimate of small error. Obviously, the lower the signal level, the more integration time required. The problem is that the signals received at different antennas travel through the Earth's troposphere and therefore are subjectedto different delay. These tropospherícd elaysv ary on a relatively short timescale, resulting in less correlation for longint egrations. Anillu stration is provided in Figure 9 for a fixed combined symbol SNR at -5 dB/Hz, with equal aperture antennas separated by a baseline of 1 - 10 km [15, 16]. At X-band, the tropospheric limit for a 20-degree correlation error is about 20 seconds. The operating region is the triangular area in the lower right corner of Figure 9. It is upper-bounded by the tropospheric noise and lower bounded by thermal noise. Note also that the graph is expressed in terms of symbol rate, rather than in received signal to noise ratio. Given a fixed symbol SNR, these two quantitiesare equ ivalent.

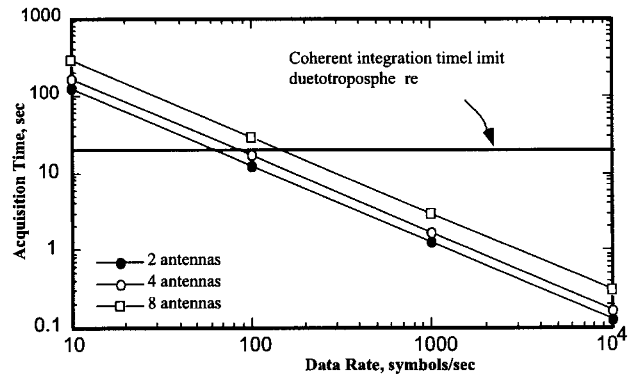



**Figure 9**Li mitso fco rrelation integration time.

Care must also be given toward the use of correlation measurements. Invalid cross correlation arises when one or both signals encounter problems. For example, one antenna could be mis-pointed, or the spacecraft could go behind a planet. As in any control feedback system, care must be given to the design so that bad estimation of the error signal does not drive the system away from a stable condition. This prevention is achieved with a filter on the FSC correlationest imates.

*Delayco mpensation*

Thedel ayco mpensationp rocessis d onein two s teps. First, eachFS Ris p rovided withtwo se tso fd elay predicts,o ne fort herefer encean tenna,th eo ther forth eant ennau nder processing. Usi ngap redict model,t heF SRremo vesa majority ofdi fferentiald elays ot hatits si gnalca nb e alignedw ith the reference. Thesep redictsa re computed basedo n thesp acecrafttraject oryan dth elo cationso f trackingan tennas. Thes econd stepin volves minor correctionb asedon resi dualerrorb eing measuredf romth e correlationi nth eF SCan dfed ba ckt ot heF SR.

Over the track, the relative position of different antennas in the array changes with respect to the spacecraft. The delay of the non-reference signal varies relative to that of the reference. The relative delay is corrected by adjusting the physical delay line in the non-reference FSR. Since such adjustment is only possible with positive values, a delay bias is introducedto all antennas.Th ebi as is typicallys etat a value at least equal to the maximum delay amongarr aying antennas. It is later corrected in the followingtelem etryand radiometricproces sing, with proper adjustmenti nth e Earth-receivedti metagso ftelem etry,Do ppler,an drang ingd ata.

Anotherco nsiderationis th ed eterminationo fdel ay. In orderto arrive att hec orrect determination ofrelati ve delay betweentwo an tennas,b oths idebandan dcar rier informationaren eeded.Th ereaso n isd ueto th e2 $\pi$ ambiguity inth eph ase differencefrom u pperan dl ower sidebands.Th esi debandm easurement alonecan o nlyp oint toas eto f possibled elays ofm odulol /(2*$f_{sb}$),wh eref $_{sb}$is thesi debandfrequ ency.Am ongth esev alues, onlyt het rue delayy ieldsa stab le cross-correlatedp haseat the carrier frequency.All ot herswil lresu lti nt hec arrierph ase being monotonicallyin creased ord ecreased,in m oduloo f2 π.

*Combining*

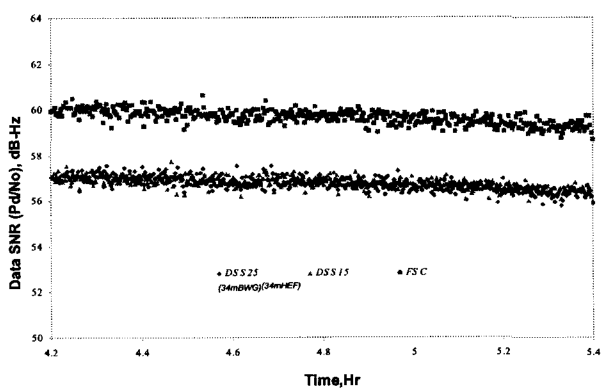
Combining is done relatively straightforward. The 16-MHz samplesfrom d ifferentFSR sa re weighted accordingt oth eir relative SNRs. The system allows disabling of certain inputs where signal is not detected, so that the non-contributingelem entwo uld notaffectt heg ainp erformance.

## 6. RES ULTS

Resultso f fieldd emonstrationsat Go ldstonew ithm issions currentlyin flig htared iscussedbe low.Em phasis will be placedo nt hea rrayg ainforte lemetryan d radiometricd ata.

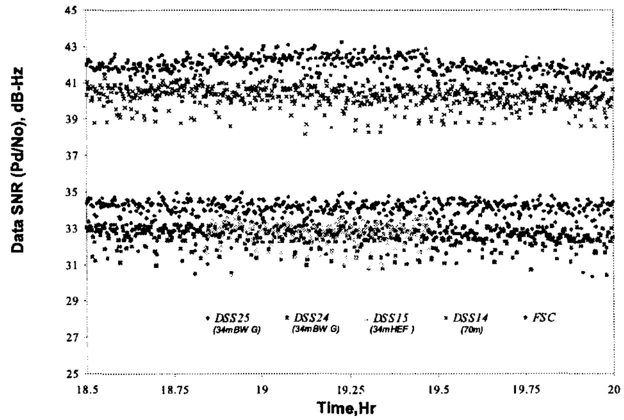
*Telemetrya rrayg ain*

Figure 10sh owst hem easurementso fi ndividuald ataS NR (Pd/No)at each ofth etwo Go ldstone 34-m antennasan dat theco mbined signald uring oneo fth eMars9 8C limate Orbitert racks.Th epro filesvary as afu nctiono fti me becauseo fth ech anging elevation.An av eragea rrayg ain of 2.9+/-0. 2 dBwas observed,co mpared to a3. 0 dB theoreticali mprovement. The0 .1d Bd ifferencei s attributed to errorin th eco rrelationi nt hep resenceo f noise aswell as signalproc essinglo ssin thehard ware. Laboratorym easurementwi thcali bratedt est signals showed thatS NR degradation,cau sedb yh ardware,is wi thin0 .2 dB.




**Figurel 0**Tw o-antennaarray wit hMa rsC limate Orbiter.

Figure 11 presents results from an array of maximum configuration. It employs all operational antennas available for X-band deep space support at Goldstone. The track was conducted with the Saturn-bound Cassini spacecraft. Relative to the performance of the 70-m antenna, the array yielded a gain of 1.8 +/- 0.6 dB. Theoretical improvement wouldh ave been2. 0d B.




**Figurel 1**Fo ur-antennaarray wit hC assini.

*Radiometrica rrayg ain*

Ranging measurementwas alsoo btainedo n ad ifferentt rack with Cassini with an array of two 34-meter antennas. The realized gain for ranging is less than that of telemetry. A 1.6 +/- 0.3 dB gain was measured, relative to 2.4 dB predicted which was confirmed by a measured 2.3 dB on telemetry. The less favorable performance is caused by the fact that ranging signal lies much further away from the carrier, compared to the telemetry subcarrier. In the presence of noise andever-chan ging Doppler frequency, the error in the phase and delay estimation of the 22 kHz sideband gets magnified when extrapolated to the 1 MHz rangings ignal.

## 7. CONCLUSIONS

In summary, this paper discusses the recently deployed array capability within the NASA Deep Space Network. It provides a brief history of arraying and how this particular method of full spectrum arraying is beneficial to missions, compared to other array techniques. A general description of equipment and special considerations on signal processing are presented. Performance improvement observed with spacecraft in flight is consistent with expectation.

This new product enables the NASA Deep Space Network to provide better support to missions. It is now possible to provide extra performance in radiometric data as well as telemetry. Also, with advances in digital signal processing, the delay within the new system is no longer subjected to the phase drift of analog electronic components. This in turn eliminates the need for pre-track calibration that was often required with past equipment, resulting in an easy-to-operateand m ores chedule-efficients ystem.

ACKNOWLEDGMENTS

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