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Standard Observing Bands: Is Now the Time to Replace S/X with X/Ka?

C.S. Jacobs, G.E. Lanyi, C.J. Naudet

Jet Propulsion Laboratory, NASA/Caltech

Contact author: C.S. Jacobs, e-mail: `Chris.Jacobs@jpl.nasa.gov`

Abstract

In this paper we will argue that the VLBI community should be developing a road map to transition from S/X to simultaneous X and Ka-band (32 GHz) observations. There are both negative and positive reasons for planning such a transition. On the negative side, we will outline concerns that S-band observations may be headed toward obsolescence. On the positive side, we will refer to evidence that X/Ka has potential for providing a more stable reference frame than S/X. We will propose timetables for a transition to X/Ka observing starting from the current status of X/Ka and plans that are now taking shape. First X/Ka fringes were obtained in 2001 with the Deep Space Network. Future plans will be discussed including a proposed X/Ka-band upgrade to the VLBA. Lastly, we will consider the need for a period of overlap between S/X and X/Ka so that the long and rich history of astrometric and geodetic VLBI is not compromised.

1. Introduction: the Motivation for Moving to X/Ka-Band

Has the time now come for the VLBI community to consider a new set of standard observing frequencies? We believe that it has. In the early 1970s astrometric and geodetic VLBI work was done at S-band (2.3 GHz). Starting in about 1978 astrometric and geodetic observations were done with simultaneous S (2.3 GHz) and X-band (8.4 GHz) observations thereby allowing one to directly calibrate plasma effects from the Earth's ionosphere and the solar plasma. This simultaneous dual band configuration has been the standard for over two decades during which time it has produced an ongoing stream of scientifically important results (*e.g.* Ma *et al.* 1998, Sovers, Fanselow, and Jacobs, 1998). Why then would one consider moving to a different set of observing bands?

There are a number of developments that are now converging to make the present time an opportune moment to consider moving astrometric and geodetic work to higher frequency bands. First, on the negative side, continued use of S-band is threatened by a radio environment which is increasingly cluttered by radio frequency interference. Second, there seems to be little chance that NASA will launch any more deep space missions that use S-band for telemetry. This is already starting to create pressure to remove S-band equipment from NASA's Deep Space Network (DSN). Both of these factors make it difficult to plan long range continuation of S/X observations for our VLBI program at JPL.

Prior to moving on to the positive motivations for moving to higher frequency bands, we would note that in recent years high frequency radio amplifiers at frequencies such as K (24 GHz), Ka (32 GHz), and Q-band (43 GHz) have become available for use by the VLBI technique. Thus it is no longer just a theoretical issue. It is now practical to make observations at these bands. These higher bands have potential for improved geodesy and astrometry to the extent that the sources become more pointlike and therefore less affected by both static source structure and the apparent proper motions induced by changing source structure. What might observers expect from moving from S/X to X/Ka-band observations? Initial evidence from K- and Q-band systems has confirmed our expectation that sources do indeed tend to become more compact at higher frequencies. The work of Boboltz *et al.* (2004, this volume) shows that sources are more compact—and therefore more astrometrically stable—at these frequencies than at X-band typically by a factor of a few. Thus there is potential for constructing references frames that are superior to the current S/X-based reference frames. These improved frames would provide improved calibrators for narrow field phase referencing work at higher frequencies.

Apart from any advantages for geodetic and astrometric work, the move to higher frequencies is being driven by the desire to achieve higher telemetry rates to interplanetary spacecraft (*e.g* Shambayati, 1999 & 2001). In particular, NASA has already started moving radio systems to Ka-band (32 GHz). The Cassini mission to Saturn is using Ka-band for radio science experiments (*e.g.* Perrot and Giordani, 1998) and the Mars Reconnaissance Orbiter, scheduled for launch in August 2005, is also being equipped with Ka-band. In addition to improving telemetry rates, the move to Ka-band will reduce the contribution of plasmas (*e.g.* Earth ionosphere and solar plasma) to the phase and group delay measurement error for single band spacecraft signals. Noting that plasma effects scale in inverse proportion to frequency squared, moving from X-band to Ka-band will reduce plasma related errors by a factor of ≈ 15.

Of course, most of the above reasoning applies to a greater or lesser extent to any frequency above X-band. So why choose Ka-band over other bands such as K-band or Q-band? Ka-band (32 GHz) is preferred over K-band (24 GHz) because it is further from the 22 GHz H_2O line; Ka-band is preferred over Q-band (43 GHz) because it is farther from the 60 GHz O_2 line. Thus the choice of the 32 GHz frequency band is an attempt to optimize atmospheric transparency. Extreme high frequencies such as W-band (86 GHz) were not chosen because of the difficulty of pointing large antennas at such high frequencies, the very short coherence time due to atmospheric turbulence (*e.g.* Linfield, 2001), and the uncertainty as to whether there are strong enough sources to be detectable within the shorter coherence times.

2. Game Plan

Having settled on Ka-band as the higher frequency band of choice, what is the plan for moving high accuracy astrometric and geodetic work to this band? While the VLBI community has taken 20 years to get S/X to its current accuracy, we expect that X/Ka-band must get to comparable accuracies in a much shorter time. Future spacecraft missions are expected to require sub-mas tracking accuracy within a few years. This is driving the need to start the process of building sub-mas reference frames at Ka-band. Yet, a full set of Ka-band antennas are not yet available. In fact, the first X/Ka-band VLBI fringe test is not scheduled until March 2004.

Because these constraints were anticipated, a plan was developed starting in 2001 (Jacobs *et al.*, 2002) to make use of then existing high frequency VLBI resources to learn as much as possible about source behavior at frequencies above X-band. The approach decided upon was to observe using the VLBA at K-band (24 GHz) and Q-band (43 GHz) in a mode that would allow both high accuracy astrometry and snapshot-based imaging. We assumed that the source properties at Ka-band (32 GHz) could then be obtained by interpolating between the 24 and 43 GHz results.

The interpolated results would then be used to determine the astrometric suitability of sources at Ka-band in advance of actual Ka-band observations. The goal in this initial stage of our plan was to learn whether there were a sufficient number of sources of sufficient strength to enable high accuracy reference frames to be built at Ka-band. Quantitatively, for spacecraft navigation applications, these goals imply a source with about 0.4 Jy or higher flux within $\approx 10^\circ$ of any point along the ecliptic plane in order to have easily detectable sources near any point along most deep space mission trajectories. The next section will briefly discuss the initial results which provide evidence that these goals are obtainable.

Our long term goal remains to move from simultaneous dual frequency S/X-band to simultaneous X/Ka-band observations. Toward that end, over the last several years, construction of X/Ka-band systems has been undertaken. Two antennas at Goldstone, California were equipped with X/Ka in 2001: DSS 13 and DSS 25. A third antenna, DSS 26, was made X/Ka ready in April 2003. The next antenna to be X/Ka equipped was DSS 55 outside of Madrid, Spain in late 2003. X/Ka capability is planned for Canberra, Australia's DSS 34 in the Spring of 2005, for Goldstone's DSS 24 in October 2006, and for Madrid's DSS 54 in August 2007. Thus there are seven antennas with X/Ka now in place or with firm plans to be so equipped within a few years.

3. Initial Observations and Results

While we envision gradually moving our focus away from single band K- or Q-band work to simultaneous X/Ka-band work, at present we must rely on the K- and Q-band results which are in hand in order to characterize the sources at high frequencies. Boboltz *et al.* (2004, this volume) and Jacobs *et al.* (2004, this volume) present the K- and Q-band results from the first two years of effort. The highlights of this work are that 230 K-band sources and 132 Q-band sources have been detected. Typically, the sources are a few times more compact at K-band than at X-band. These results indicate that there are enough strong sources to make pursuing X/Ka-band observations worthwhile.

In order to learn as much as possible as quickly as possible, short baseline tests at Ka-band have been done while the remaining parts of the long baseline system are being built. The first X/Ka-band fringes were obtained on 30 September 2001 on the 10 km DSS 13 to DSS 25 baseline within the Goldstone California tracking complex using connected element interferometry (CEI) [1]. We obtained usable group delays for 54 of 120 scheduled observations. The strongest Ka-band detection was for the source DA 55 for which the measured SNR was 166. This test confirmed that the receiving systems worked at Ka-band but that it was desirable to improve the antenna pointing—work which is currently underway.

We would also note that the group in Kashima, Japan has had a Ka-band system (31.7 GHz to 33.7 GHz) on its 34m antenna since about 2002 (Nakajima *et al.*, 2003). This system is advertised as having a 150 K system temperature. We have been exploring the potential for collaboration between the Kashima Ka-band system and the NASA Ka-band systems.

4. Future Plans

What is the next step toward broad use of X/Ka for astrometry and geodesy? Encouraged by the sucess of the so-called "RDV" sessions (*e.g.* Gordon, 2002; Sovers *et al.*, 2002) which use the VLBA at S/X, a dialogue has been initiated between NASA and the VLBA regarding the possibility of equipping VLBA antennas with simultaneous X/Ka-band systems. While it would be technically desirable to have all ten VLBA antennas equipped with X/Ka before the Mars Reconnaissance Orbiter scheduled launch in August 2005, there are no such plans yet in place.

There is, however, solid technical interest from NASA and VLBA representatives who have started initial estimates of cost and schedule. While for highest accuracy it is highly desirable to have simultaneous X and Ka-bands, detailed cost vs. benefit analysis for a single band Ka system vs. a simultaneous dual band X/Ka system remains to be completed. Issues such as feed design, the assignment of a space on the feed ring of the VLBA antenna, and Ka-band phase calibration generators are amongst the items needing further study.

5. Proposed Roadmap for S/X to X/Ka Transition

As discussed at the start of this paper, we see many potential benefits of moving high accuracy astrometric and geodetic work to X/Ka-band. However, we must at the same time retain the great value of over 20 years of proven S/X results (*e.g.* Ma *et al.*, 1998; Sovers, Fanselow and Jacobs, 1998). Thus it is highly desirable to have a period of overlap during which the accuracy of new X/Ka systems could be verified against existing S/X systems. This should include sufficient overlap of geodetic measurements to insure continuity of the VLBI based terrestrial frames. We suggest that 5-10 years of overlap would be a reasonable goal. We anticipate that by 2007 NASA's X/Ka systems will be mature enough to produce high accuracy astrometry and geodesy. Thus we suggest that the period of overlap would start around 2007 and last to at least 2012 and preferably to 2017.

6. Conclusions

We have presented the motivation for moving astrometric and geodetic observations from S/X to X/Ka-band. We have outlined a plan for establishing high frequency astrometry and geodesy starting with work at K- and Q-bands. This preliminary work has already extended the celestial frame to K-band (230 sources) and Q-band (132 sources) at the sub-mas level. Furthermore, interpolation of the these results suggests that similar results should be obtainable at the intermediate Ka-band. There are currently four antennas in NASA's Deep Space Network equipped with X/Ka-band with seven antennas expected by 2007. Kashima currently has a Ka-band system and the VLBA has begun study of proposals to install either Ka or X/Ka-bands systems in its antennas. Thus there is a potential for having as many as 18 Ka-band equipped antennas within a few years. First fringes have been obtained at X/Ka-band on a short baseline connected element interferometer and long baseline VLBI tests are planned for March 2004. All of these developments suggest that X/Ka-band VLBI is feasible.

We are optimistic about the future of X/Ka-band VLBI for astrometry, geodesy, and spacecraft tracking. We believe that there is great potential for a major step forward in these fields. Therefore, we encourage other VLBI groups to consider joining the move from S/X to X/Ka-band.

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